SCS
NATIONAL
ENGINEERING
HANDBOOK

SECTION 3

# SEDIMENTATION



U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

# PREFACE

These Chapters of Section 3, Sedimentation, SCS National Engineering Handbook, are the result of the combined efforts of many SCS employees Many geologists and engineers throughout the Service participated in the review and have improved the original material with their suggestions. The following SCS geologists were the principal authors:

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Note: This issue is for in-Service use and the material contained is not released for publication.

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SECTION 3

SEDIMENTATION

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SEDIMENTATION

# CHAPTER 4 - TRANSPORTATION OF SEDIMENT BY WATER

## Symbols

| Symbol | Description | Units |
|---|---|---|
| A | Area of flow cross section | sq ft |
| B or b | Width | ft |
| D | Depth | ft |
| d or $d_{50}$ | $d_{50}$ size of bed material | mm, in. or ft |
| $d_m$ | The Meyer-Peter "effective grain diameter" | ft or mm |
| $d_s$ | Particle size (unspecified) | mm, in. or ft |
| f | Darcy-Weisbach friction coefficient $\frac{8gRS}{U^2}$ | |
| g | Acceleration due to gravity, assumed constant and equal to 32.2 | ft/sec/sec |
| $k_s$ | Representative grain size | ft |
| Q | Water discharge | cfs |
| $Q_B$ | Bed-load discharge | ton/day or lb/sec |
| $Q_T$ | Total bed-material discharge | ton/day or lb/sec |
| q | Unit water discharge | cfs/ft of channel width |
| $q_o$ | Unit water discharge just sufficient to move bed material | cfs/ft of channel width |
| $q_B$ | Unit bed-load discharge | ton/day or lb/sec/ft of channel width |
| $q_T$ | Unit bed-material discharge | ton/day or lb/sec/ft of channel width |

| Symbol | Description | Units |
|---|---|---|
| R | Hydraulic radius | ft |
| R' | Hydraulic radius with respect to the grain | ft |
| R" | Hydraulic radius with respect to dunes and bars | ft |
| S | Slope | ft/ft |
| $S_w$ | Water surface slope or hydraulic gradient | ft/ft |
| $S_o$ | Bed slope | ft/ft |
| $S_e$ | Energy gradient | ft/ft |
| $S_s$ | Specific gravity of sediment (dimensionless) | |
| T° | Water temperature | °F or °C |
| $u_*$ | Shear velocity $\sqrt{gDS_e}$ | ft/sec |
| $u_*'$ | Shear velocity associated with grain roughness | ft/sec |
| U or V | Mean velocity | ft/sec |
| w | Fall velocity of sediment particles | ft/sec |
| $\gamma$ | Unit weight of water | $lbs/ft^3$ |
| $\gamma_s$ | Unit weight of sediment, dry | $lb/ft^3$ |
| $\Delta_\gamma$ | Difference between the specific weights of sediment and water | $lb/ft^3$ |
| $\delta$ | Thickness of laminar sublayer | ft |
| $\Theta$ | A dimensionless form of the bed shear $\tau_o$ | |
| $\nu$ | Kinematic viscosity | $ft^2/sec$ |
| $\mu$ | Dynamic viscosity | $lb\text{-}sec/ft^2$ |
| $\rho$ | Density of water | $slugs/ft^3$ |
| $\rho_s$ | Density of sediment | $slugs/ft^3$ |
| $\Psi$ | A dimensionless parameter indicative of the ability of a flow to dislodge a given particle size | |

| Symbol | Description | Units |
|---|---|---|
| $\Phi$ | A dimensionless parameter describing the intensity of transport of bed material in a given size range | |
| $F_N$ or $F_D$ | Froude number; equal to $\frac{U}{\sqrt{gD}}$ | |
| $R_N$ | Reynolds number; equal to $\frac{UD}{\nu}$ or $\frac{8UR}{\nu}$ | |
| $\tau_o$ | Total bed shear stress | $lb/ft^2$ |
| $\tau_c$ | Critical tractive stress associated with beginning of bed movement | $lb/ft^2$ |
| $\tau'$ | Shear stress associated with grain resistance | $lb/ft^2$ |
| $\tau''$ | Shear stress associated with irregularities in bed and banks | $lb/ft^2$ |

## Terms

Antidunes: Bed forms of curved, symmetrically shaped sand waves that generally move upstream.

Armor: A layer of particles, usually gravel size, that may cover the surface of the bed as a coarse residue following erosion of the finer bed materials for a particular flow range.

Bars: See dunes.

Bed forms: Generic terms used to describe irregularities on the bed. Includes ripples, dunes, etc.

Bed load: Bed particles moving in the bed layer. This motion occurs by rolling, sliding, and sometimes by jumping.

Bed-material load: Rate of transport of particles found in appreciable quantities in the bed.

Coefficient of viscosity: The ratio of the shear stress to the velocity gradient perpendicular to the direction of flow of a Newtonian Fluid or the ratio of shearing stress in a moving liquid to the rate of deformation.

Coefficient of kinematic viscosity: The ratio of the coefficient of viscosity to the density of a fluid.

Dune: A sand wave of approximately triangular cross section in a vertical plane in the direction of flow with gentle upstream slopes and steep downstream slope. It travels downstream as a result of the movement of the sediment up the upstream slope and the deposition of part of this material on the downstream slope.

Fall diameter or standard fall diameter: The diameter of a sphere that has a specific gravity of 2.65 and the same terminal velocity as the particle of any specific gravity when each is allowed to settle alone in quiescent distilled water of infinite extent and at a temperature of 24°C. The terminal velocity is that obtained by a particle when the resistance of the water has become equal to the force of gravity.

Flat or plane bed: A bed without elevations or depressions larger than the maximum size of the bed material.

Laminar flow: Low velocity flow characterized by the condition that layers of fluid slip over contiguous layers without appreciable mixing.

Ripples: Small triangular-shaped bed forms that are similar to dunes but have much smaller amplitudes and lengths.

Slug flow: Characterized by steep fronted waves whose velocity is smaller than the surface velocity of the flow.

Standing waves: A type of wave in which the surface of the water oscillates vertically between fixed nodes without progressing. A wave usually conforming to and resulting from stream bed sand dune movement.

Suspended load: Particles moving outside the bed layer. Includes suspended bed material and wash load.

Turbulent flow: A state of flow of water wherein the water is agitated by cross currents and eddies.

Uniform flow: A flow that is constant in both time and distance along the stream lines.

Wash load: That part of the total sediment load which consists of grain sizes finer than those of the bed.

## General

An understanding of the principles of sediment transport by flowing water is essential to the interpretation and solution of many problems. The characteristics of water and sediment individually and in their interaction directly influence the type and volume of material eroded and transported and the condition of deposition when and where it occurs. Problems of channel stability including erosion or aggradation and predictions of performance of proposed channel improvements are among those that require knowledge and use of procedures pertaining to sediment transport. Information derived from the use of sediment transport procedures is used in determining requirements for coarse sediment storage in debris basins and other types of structures.

This chapter includes a discussion of the characteristics of water in the turbulent range as a medium for initiating the movement and transportation of sediment. The reaction of the material on the stream bed

to the hydraulic forces exerted, and the effect on the depth of flow and velocity and on the rate of bed-material transport are described. Formulas or procedures designed to predict rates of bed-material transport per unit discharge are given and evaluated as to their reliability. Recommendations are made concerning the application to channel problems related to bed-material transport. The chapter concludes with a discussion of the mechanism of suspended load transport and a method of computing its watershed yield from measurements and flow duration data.

## Factors Which Influence Transportation of Sediment

The mechanism of entrainment and the rate at which sediment is transported are dependent upon characteristics of the transporting medium and of the particles, and on their availability or resistance to movement and transport.

### Characteristics of water as the transporting medium

The interrelated properties and condition of water which determine its capacity to entrain and move sedimentary particles include density, viscosity, temperature and acidity or basicity.

Density. - Density is the ratio of mass of water to its volume. Increasing the temperature of a given mass of water will increase the volume of water and change the density. With a change in temperature from 40°C. to 100° C. a given volume of water will increase to 1.04 its original volume. In dealing with large volumes of moving water changes in density due to temperature changes are generally ignored.

Temperature. - Temperature is a measure of heat energy produced by molecular agitation. Changes in temperature indicate and result in changes of physical and chemical properties of fluids.

Viscosity. - Viscosity is the cohesive force existing between particles of a fluid which causes the fluid to offer resistance to a relative sliding motion between particles. Under ordinary conditions of pressure, viscosity varies only with temperature. A decrease in water temperature from 80° F. to 40° F. increases the viscosity about 80 percent.

Acidity or basicity. - The negative logarithm (base 10) of the hydrogen ion concentration is termed the pH value. A pH value of 7.0 indicates neutral water. Values of pH less than 7.0 denote acid water; values greater than 7.0 denote a basic solution.

Acid waters may aid in the formation of colloidal masses of very fine sediments (flocculation) which will move with currents.

The most prominent factors affecting sediment transport are viscosity and temperature.

Changes in viscosity affect the fall velocity of suspended sediment and thereby its vertical distribution in turbulent flow (Colby and Scott, 1965, p. 62). An increase in viscosity lowers the fall velocity of particles that are small, particularly those in the range of very fine sand and silts.

Evidence indicates that a substantial decrease in water temperature and as a consequence, the increase in viscosity, results in a smoothing of the bed configuration, a lowering of the Manning "n" roughness coefficient, and an increase in velocity in a sand bed stream (U. S. Corps of Engineers, MRD No. 13A, 1968).

## The laminar sublayer

In turbulent flow, a thin layer is formed adjacent to the bed within which the flow is laminar, because the fluid particles in contact with the bed do not move. This thin layer is known as the laminar sublayer. The higher the velocity or the lower the viscosity, the thinner is this sublayer.

While laminar flow is intimately related to the fluid property of viscosity, turbulent flow is influenced by a number of factors. In laminar flow filaments of water follow parallel paths, but in turbulent flow the paths of particles crisscross, intersect, and touch, causing a mixing of the liquid. A criterion of flow as to whether it is laminar or turbulent is defined by the Reynolds number $R_N$ developed by Osborne Reynolds in 1883. This is a ratio of inertial and shear forces on the fluid particle. At low Reynolds numbers viscous forces are dominant but decline to little significance with high Reynolds numbers indicating the dominance of inertial forces.

The association of laminar flow with viscosity, and turbulent flow with inertia bear the same relationship whether the fluid is moving or a particle is falling through the fluid at rest. A small particle of sediment, such as very fine sand, settling from suspension in still or flowing water, moves so slowly as to sustain laminar flow lines in relatively viscous media. Inertial force which is the product of mass times acceleration becomes increasingly important as grain size exceeds about 0.5 mm. and viscous forces decline in significance.

## Characteristics of transportable materials

The characteristics of discrete particles are discussed in chapter 2 of this section of the handbook. The entrainment and transport of granular materials depend on the particle size, shape, specific weight, and position with respect to each other. The resistance of cohesive materials depends largely upon the cohesive forces binding the individual particles. These forces may be attributed to several factors, including the amount and kind of clay minerals, the degree of consolidation or cementation, and the structure of the soil mass.

## Mechanism of entrainment

Forces acting on discrete particles. - Turbulence is a highly irregular form of motion of a flowing fluid characterized by the presence of eddies. The eddies are formed to different degrees as a function of boundary roughness and geometry of the channel and sustained by energy supplied by the main flow. The eddies penetrate the laminar sublayer which forms along the bed due to viscous drag of the water along the boundary. Streams with which the Soil Conservation Service is concerned are almost always turbulent.

Discrete particles resting on the bed are acted upon by two identifiable components of the general hydraulic force exerted within eddies of turbulent flow. These component forces are (a) parallel to the flow (drag forces), and (b) perpendicular to the flow (lift forces). These result from pressure gradients created by the flow at the front and at the back sides of the particle. A lifting force results from the pressure differences on the upper and lower surfaces. If the lifting force exceeds the restraining forces due to the particle's immersed weight and the interference of neighboring grains, it will be placed in motion.

The turbulence is random and irregular, thus discrete particles tend to move in a series of short intermittent bursts, each covering a small area. At each burst, many grains move simultaneously, then the movement subsides until another burst occurs. The frequency and extent of movement increases with the intensity of turbulence and after a certain point the particle may be projected into the flow as suspended load (Sutherland, 1967, p. 6184). The coarser the particles, however, the greater the tendency for a rolling motion to be initiated and to persist.

## Tractive force

The interest and experimentation in determining the forces that act on particles on the bed of a stream were performed largely for the purpose of predicting the stability of the channel. Once transport has begun, more advanced methods are necessary to describe it. The assumptions of early theorists regarding the forces required to initiate motion were later substantiated by experimentation.

The instantaneous interaction between turbulent flow and discrete sediment particles resting on the bed has been described briefly above. In practical application, however, it is more convenient to deal with time average values of the force field generated by the flow near the bed. Then the forces normal to bed having a time average equal to zero may be eliminated and the only ones that need be considered are those tangent to the bed. The time average of these forces is the "tractive force" which, when taken over a unit surface area, becomes the "tractive stress." The dynamic response of the boundary upon the flow has the same magnitude, but opposite direction, the

friction force corresponding to the tractive force and the shear stress to the tractive stress. In a channel reach bounded by two end sections, the mean value of this stress is equal to the weight of the water prism in the reach times the energy gradient, divided by the wetted boundary surface in the reach. In an infinitely wide channel this stress or force per unit area of bed is expressed as $\tau_o = \gamma D\, S_e$ when the terms are as defined previously.

Determination of critical tractive stress

The most widely used and reliable evaluation of tractive stress related to the initiation of motion is that developed by Shields (1936). The theoretical concepts, supported by experiments, resulted in a plot of $\frac{\tau_c}{\gamma(\frac{\gamma_s}{\gamma} - 1)d_s}$ against $\frac{u_* d_s}{\nu}$. The former expression is an entrainment function and the latter is a Reynolds number which indicates intensity of flow turbulence in the vicinity of the particle. The Shields data are based on particles of uniform size on a flat bed. The Shields experiments indicated that beyond a certain value of the Reynolds number $\frac{u_* d_s}{\nu}$ the value of the parameter $\frac{\tau_c}{\gamma(\frac{\gamma_s}{\gamma} - 1)d_s}$ remains constant. Therefore, in this region the critical tractive stress is proportional to the grain size.

Data on critical tractive stresses as observed by a number of investigations have been assembled by Lane (1955, p. 1253). These data show that the critical tractive stress in pounds per square foot is equal to $\tau_c = 0.5\ d_{75}$, where $d_{75}$ is defined as the size in inches of which 25 percent by weight is larger. The limiting or allowable tractive stress has been obtained from observations on a system of canals (Lane, 1955, p. 1244). These data show that the limiting tractive stress in pounds per square foot is equal to 0.4 of the $d_{75}$ size in inches for particles that exceed 0.25 inches in diameter. For finer particles there is a considerable variation in experimental results, probably due to the range of conditions which existed. These include differences in the interpretation of initiation of sediment movement, temperature of the water and configuration of the bed. Critical conditions for initiation of transport have sometimes been judged on the number or frequency with which particles start to move. For example, one observer's criterion uses the time when grains are set into motion at any chosen spot on the bed every two seconds (Sutherland, 1967, p. 6184).

Figure 4-1a is a plotting of the critical tractive stress as related to the mean particle size or to the $d_{75}$, using data of Shields and of Lane (ASCE Proc. No. 4738 HY2, 1966, p. 299). Differences in critical tractive stress due to temperature variation, and the Reynolds numbers at various tractive stress levels are shown on the figure. The wide departure of Lane's curve in Figure 4-1a (for critical tractive stress) from the others is believed to be due to Lane's use of Fortier and Scobey's data (1926) from canals after aging. The stability of some soils is increased by the effects of aging on the structure, consolidation or cohesion.

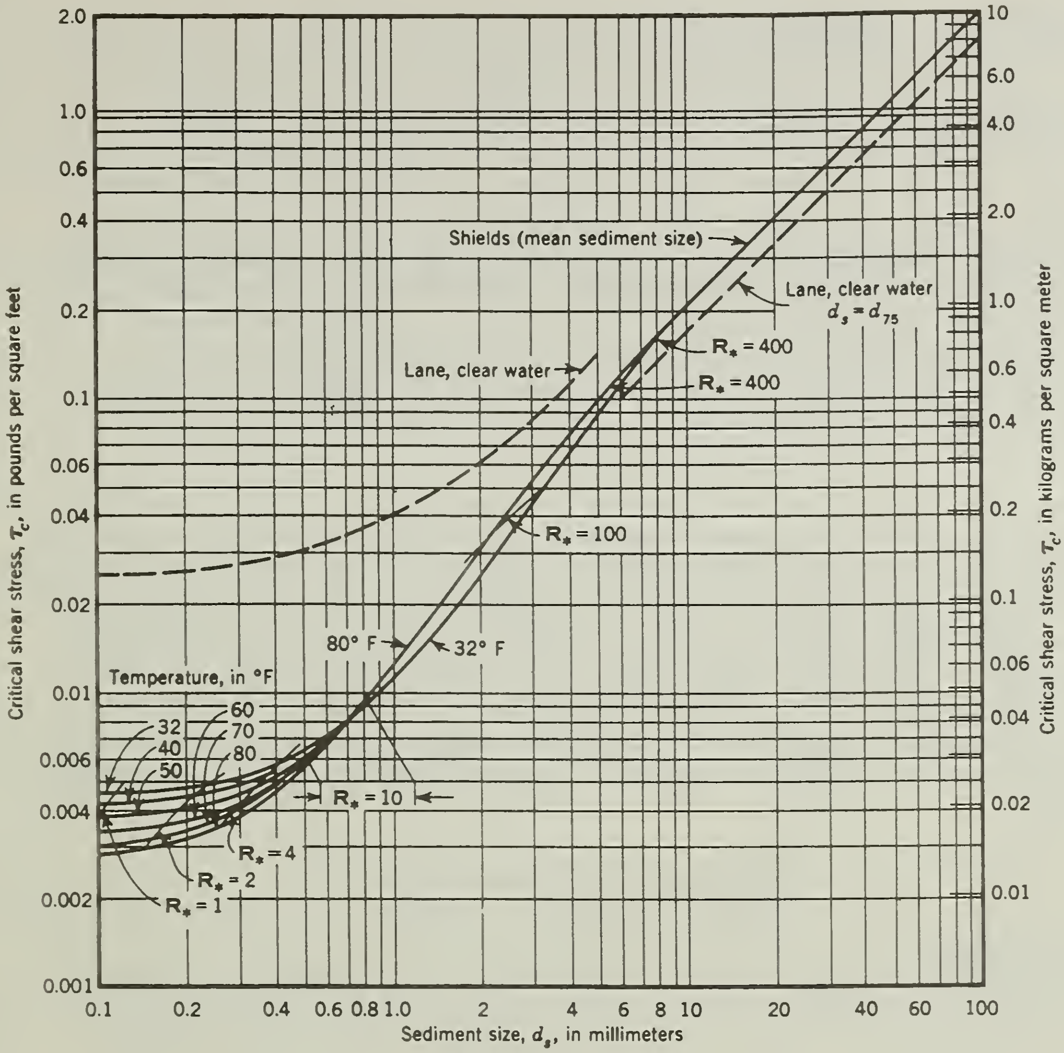


Fig. 4-1a.- Critical shear stress for quartz sediment in water as function of grain size (From Shields 1936 and 1955, A.S.C.E.Jour.Hyd.Div., July 1969, p.299)

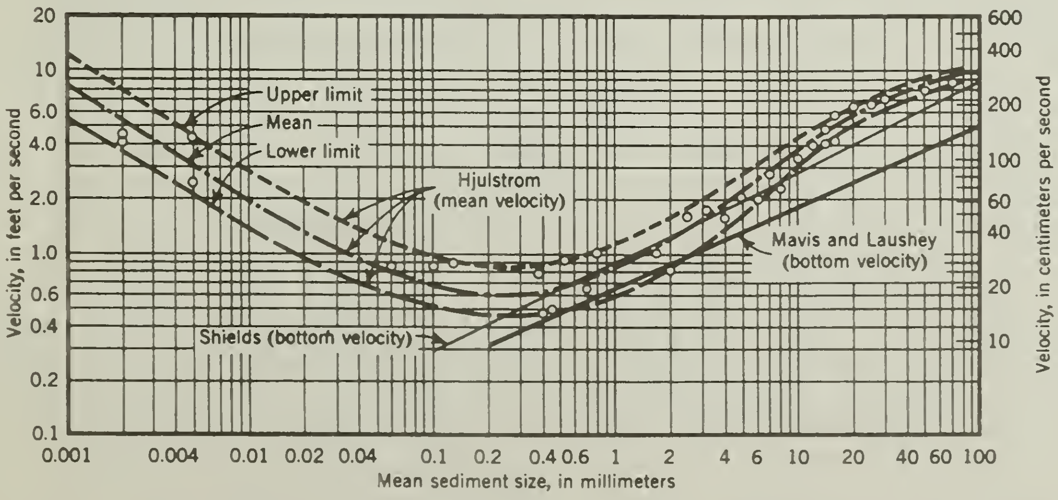


Fig. 4-1b.- Critical water velocities for quartz sediment as function of mean grain size (A.S.C.E.Jour. Hyd. Div., July 1969, p.299

Fig. 4-1

Determination of critical velocity

Another method of establishing a criterion of stability is the critical velocity at which particles begin to move. Both mean velocity and bottom velocity have been the subject of study. Figure 4-1b shows critical water velocities or the velocities at which particles in the bed begin to move, as a function of mean grain size. There has been less agreement on the critical velocities initiating movement than on critical tractive stress, probably because bottom velocities increase at a slower rate than the mean velocity as the depth increases. Critical conditions for the initiation of movement can be more directly expressed in terms of tractive stress while critical mean velocity must be related to depth of flow and variation of velocity with depth.

The correct determination of critical values for tractive stress or velocity is important when considering channel stability problems where there is to be no significant movement of the boundary material. In defining the beginning of sediment transport, their significance is in the magnitude and duration of flows exceeding these values. For instance, a prolonged flow that is slightly in excess of the critical values may have little significance in terms of volume of transported bed material. On the other hand, a short duration flow substantially in excess of critical could transport a large volume of sediment.

## Hydraulic Considerations

Fixed boundaries

Velocity-stage-discharge relationships for stream channels with fixed boundaries have long been satisfactorily predicted with appropriate selection of "n" values in Manning's and other related formulas.

Movable boundaries

The study of the hydraulics of movable boundaries has been devoted to two general problems. Interest has been primarily in obtaining methodology for prediction of friction coefficients and thereby the correct velocity, stage and discharge relationships for purposes of channel design. The need for these data as a key element of procedures for predicting sediment transport has added incentive to investigations. Because of the above considerations, the changes in bed form produced on a movable bed and consequently of its frictional characteristics has been one of the most intensively studied flow phenomenon. The body of literature on this subject generally describes the sequence of change in bed configuration that may occur as the flow and transport intensity increases in magnitude. There may be ripples, ripples on dunes, or dunes at low transport rates and anti-dunes or a flat bed with rapid sediment movement. These bed forms have been observed in sand bed flumes and streams with a $d_{50}$ size finer than 1.0 mm. Indications are that there is a decrease in the variety of bed forms with coarser material.

Pioneering efforts in investigating the hydraulics of movable beds led to a division of the hydraulic radius into two parts. One was termed the radius due to the roughness of the grain size of the individual particles (R') and the other the radius due to the roughness of the bed configuration (R") (Einstein, 1950, p. 9; Einstein and Barbarossa, 1952, p. 1126).

Einstein and Barbarossa from field observations developed a graph relating the dimensionless ratio $\frac{U}{u_*''}$ (where $u_*'' = \sqrt{gR''S_e}$) to Einstein's flow intensity parameter $\Psi$. The implication was that for a given set of conditions it would be possible to develop a unique stage-discharge relationship and thus predict the hydraulics of a channel with movable boundaries. Vanoni and Brooks (1957) presented a partial graphical solution to the friction equation from which R' is determined.

Another procedure for prediction of hydraulic behavior in movable channel beds was based on the division of slope S into two parts, S' and S" (Meyer-Peter and Muller, 1948, p. 39). In this approach S' is the energy gradient associated with the grain size of the bed material under a certain velocity and depth, excluding form resistance, and S" is the additional gradient pertaining to bed form resistance. This division of slope was adopted by Alam and Kennedy (1969) whose procedure is explained in the appendix to this chapter.

A similar hydraulic consideration sometimes used as a part of the procedure preliminary to sediment transport computations is the treatment of bank friction as a distinct entity from that of the bed. Such an approach employing Manning's friction equation is included as part of the procedure in the Einstein bed load function (to be presented later).

## Movement of Bed Material

In this discussion the term "bed-material load" is defined as the rate of transport of that part of the total sediment load (suspended plus bed load) comprised of grain sizes encountered in the bed material. The part of the total load or more specifically of the suspended load that consists of grain sizes not encountered in the bed material constitutes the wash load. Sand size particles that may constitute the exclusive or major portion of bed material travel either on the bed as bed load or in suspension. Figure 4-2 (Cooper and Peterson, 1970) illustrates how the total sediment load is classified into bed load, bed-material load, and wash load. Evaluation techniques are not sufficiently refined to accurately predict which portion of the bed-material load moves in suspension or as bed load under specific hydraulic conditions, nor does it seem essential to the general solution of sediment transport problems that this separation be established.

<table>
<tr><td colspan="2"></td><td colspan="2">Classification System</td></tr>
<tr><td colspan="2"></td><td>Based on mechanism of transport</td><td>Based on particle size</td></tr>
<tr><td rowspan="3">Total sediment load</td><td>Wash load</td><td rowspan="2">Suspended load</td><td>Wash load</td></tr>
<tr><td>Suspended bed-material load</td><td rowspan="2">Bed-material load</td></tr>
<tr><td>Bed load</td><td>Bed load</td></tr>
</table>

Fig. 4-2.- Sediment load classification (Adapted from Cooper and Peterson, 1970, P. 1881)

Transport rates of sand and gravel have been determined both by direct measurements and by computational procedures. The measurement of rates of transport in natural streams have been quite few in number, due chiefly to the problem of obtaining representative measurements. Sampling equipment established in or lowered to the bed have a tendency to alter the direction of flow filaments and the sediment concentration. The more accurate determinations have been made by installations which are constructed to withdraw representative samples of the water-sediment mixture during specific intervals of time. Another procedure has been the sampling of the total load as the flows move over a sill at an elevation uniform with the slope upstream.

The attention devoted toward development of procedures for predicting rates of transport is indicative both of the problem of obtaining measurements and of the large number of variables which may influence the consistency of results. Flume studies offer the most favorable opportunity for controlled experiments and the exclusion of some of the variables. These have, therefore, become the primary basis for establishing relationships between stream discharge and bed-material load since the facilities for flume installation have been available.

Bed-material transport formulas

The earliest formula still in some use is that of Duboys, who published the results of studies of the Rhone River in 1879. Duboys initiated a concept that is common to many formulas when he included in his derivation the assumption that the rate of sediment transport is proportional to the tractive stress in excess of the critical value required to initiate motion. It is given here as the original of a concept upon which a number of later formulas were partially based.

$$q_T = \Psi\tau_o(\tau_o - \tau_c) \qquad (1)$$

where $q_T$ is the rate of sediment transport per unit width of stream and $\Psi$ (not to be confused with Einstein's $\Psi$) is a coefficient dependent upon the character of sediment.

$\tau_c$ in the above equation is not the same as Shields but is a value obtained in experiments.

In the early part of the twentieth century there were initiated a number of flume studies of sand transport, including that of Shields, who is most widely known for the development of criteria for initiation of movement. Probably the most extensive early investigation of sediment transport in flumes was that of Gilbert on the campus of the University of California about 1910 (Gilbert, 1914). Description of a number of transport phenomena resulted from those experiments but no general formula.

Of the following formulas described, the Schoklitsch, Meyer-Peter, Haywood, and Meyer-Peter and Muller are bed-load formulas or those determining the discharge of material moving along the streambed. The Einstein Bed-Load Function, the Engelund-Hansen Procedure and the Colby Procedure determine the rate of bed-material discharge, both that moving along the bed and in suspension.

The Schoklitsch formula. - The work of Schoklitsch (Shulits, 1935, p. 644 and Shulits and Hill, 1968, p. S34-1) resulted in the development of one of the more extensively used empirical formulas. It was developed to some extent from experimental data of the author but chiefly from the flume measurements of Gilbert cited above.

The Schoklitsch formula in English units is:

$$q_B = \frac{86.7}{\sqrt{d_{50}}} S_e^{3/2} (q - q_o) \qquad (2)$$

in which $q_B$ is pounds per second per foot of width

$d_{50}$ is in inches

$q_o$ in this instance equals $0.00532 \dfrac{d_{50}}{S_o^{4/3}}$

In describing the formula Shulits recommended that a cross section in a straight reach of river be considered where the depth of water is as uniform as possible and the width changes as little as possible with stage.

As described by Shulits, the Schoklitsch formula was demonstrated to fit Gilbert's measurements with uniform particle sizes of about 0.3 mm to 7 mm and slopes ranging from 0.006 to 0.030 ft/ft for the small particles and 0.004 to 0.028 ft/ft for the larger.

The Meyer-Peter formula. - In 1934 the Laboratory for Hydraulic Research at Zurich, Switzerland published a formula for bed-load transport based on flume experiments with material of uniform grain size. The original analysis of the Zurich and Gilbert data on uniform particles ranging in size from about 3 to 28 mm was supplemented by studies of particle mixtures up to 10 mm in size and of various specific gravities.

The Meyer-Peter formula in English units is in the form

$$q_B = (39.25\ q^{2/3}\ S_o - 9.95\ d_m)^{3/2} \qquad (3)$$

where $d_m$ is expressed in feet.

The new term in this formula is $d_m$, which Meyer-Peter terms the "effective diameter" for the purpose of identifying the characteristic size of a composite sample. To obtain this value, the size distribution curve of a bed material mechanical analysis is divided into a convenient number of size fractions, and the mean size and weight percentage of each fraction is determined. The sum of the products is then divided by 100.

The Haywood formula. - The Haywood formula is based on the Gilbert flume data and comparison with the data from the U. S. Waterways Experiment Station, Vicksburg, Mississippi. In his evaluation, Haywood (1940) made an adjustment in Gilbert's data to account for sidewall resistance. He assumed that the discharge effective in moving bed load is midway between that of walls which offer no resistance and the walls having the same resistance as the bed. The author shows the close relationship to the Schoklitsch formula which is based on some of the same data. Haywood believes that his formula is in substantial agreement with Schoklitsch for relatively large rates of bed-load movement and that it is much more accurate for very small rates of movement. The size of maximum application he considers to be 3 mm. Haywood regarded his formula as a modification of the Meyer-Peter formula.

The Haywood formula is of the form:

$$q_B = \left[\frac{q^{2/3}\ S_o - 1.20\ d^{4/3}}{0.117\ d^{1/3}}\right]^{3/2} \qquad (4)$$

where d is the $d_{35}$ expressed in feet.

The Meyer-Peter and Muller formula. - The Meyer-Peter and Muller formula is based on the data obtained from a continuation of the experiments which resulted in the Meyer-Peter formula. An extension in the range of variables, particularly slope, was made. The following is a list of slopes and particle sizes.

| Slopes (ft/ft) | Effective grain diameter (mm) |
|---|---|
| .004 - .005 | 0.14 |
| .02 - .03 | 1.7 - 2.0 |
| .08 | 4.4 |

A few tests were run with slopes as high as 20 percent and sediment sizes as coarse as 30 mm. The authors state explicitly that their work was on bed-load transport by which they mean the movement of sediment rolling or jumping along the bed. Transport of material in suspension is not included (Meyer-Peter and Muller, 1948, p. 39).

The Meyer-Peter and Muller formula as translated by Sheppard (1960, p. 18):

$$q_B = 1.606 \left[3.306 \left(\frac{Qs}{Q}\right)\left(\frac{d_{90}^{1/6}}{n_s}\right)^{3/2} D\ S_e - 0.627\ d_m\right]^{3/2} \qquad (5)$$

where $d_{90}$ is expressed in millimeters, otherwise $d_m$ is explained with reference to the Meyer-Peter formula and is in millimeters.

Nomographs are available for the determination of $\frac{Qs}{Q}$ which is a ratio of the discharge quantity determining bed-load transport to the total discharge and $n_s$, which is a Manning "n" value for the bed of the stream. The formula as a significant departure from the previously cited formulas includes a ratio of the variable form roughness of the bed to the grain roughness of the surface.

The Einstein bed-load function. - In 1950 Einstein's "Bed-Load Function" was published and has since that time caused a major impact on the investigations of the hydraulics and sediment transport characteristics of alluvial streams. The author has described the function as giving "rates at which flows of any magnitude in a given channel will transport as bed load the individual sediment sizes of which the channel is composed" (Einstein, 1950, p. 3). It has been developed on the basis of experimental data, theory of turbulent flow, field data, and intuitive concepts of sediment transport.

The Einstein bed-load function is a procedure that computes the bed load first, then by a process of integrating the concentration at the bed layer with the normal reflection of that concentration in the remainder of the flow depth, the procedure determines the total bed-material load.

Several new ideas were introduced into the theory of sediment transport by Einstein. Included are methods of accounting for bed friction by dividing it into two parts, one pertaining to the sand grain surface, the other to the bed form roughness, such as ripples or dunes. An additional friction factor, that of the banks, is included in the procedure for determining hydraulic behavior prior to computing bed-material transport.

Another concept introduced by Einstein in order to explain the character of the bed-load function is that statistical laws govern the motion of bed load including the probability of grain particle movement being dependent upon its size, shape, and weight, and the flow pattern. Similar laws are reported to govern the probability of distance of travel and of redeposition (Einstein, 1940, p. 30-31). Probability is included in a theoretical expression of $\Phi$, the intensity of bed-load transport in dimensionless form. The mathematical relationship between this factor and the dimensionless flow intensity, $\Psi$, another basic parameter reflecting the intensity of shear on the particle, are graphically presented as a part of the procedure for problem solution. The $\Phi$-$\Psi$ relationship has subsequently been investigated by others as an appropriate determinant of bed-load transport.

The Engelund-Hansen procedure. - Engelund and Hansen (1967) have developed a procedure for predicting stage-discharge relationships and sediment transport in alluvial streams having bed material for transport. They introduced a parameter $\Theta$ representing the ratio between agitating forces (horizontal drag and lifting force) and the stabilizing force (immersed weight of the particle). The parameter is a dimensionless form of the bed shear $\tau_0$ to be divided into two parts, $\tau'$ being the value of that portion acting directly as traction on the particle surface and $\tau''$ being the residual part corresponding to bed-form drag. This division is similar to the Einstein-Barbarossa R' and R''. The author's diagram of the relationship of bed forms to the two separations of total bed shear and to velocity is shown in Figure 4-3.

Principles of hydraulic similarity were used to develop a working hypothesis to describe resistance to flow, specifically for dune covered stream beds and bed-material discharge.

The steps used in applying the Engelund-Hansen procedure are given in some detail because it demonstrates the impact of changing bed forms on bed-material transport and because the procedure appears in a foreign journal and is not readily available for reference. Data from the flume experiments by Guy, Simons and Richardson (1966) were used to test the authors' theories. The mean sizes used in these experiments were 0.19, 0.27, 0.45 and 0.93 mm. The bed material, both in suspension and moving along the bed, was measured.

The authors present both a simplified and a more detailed series of computations. Figure 4-4 in conjunction with Figure 4-3 shows the flow regime in which a semigraphical solution, Figure 4-5, is applicable; that is, in the region of dune formation.

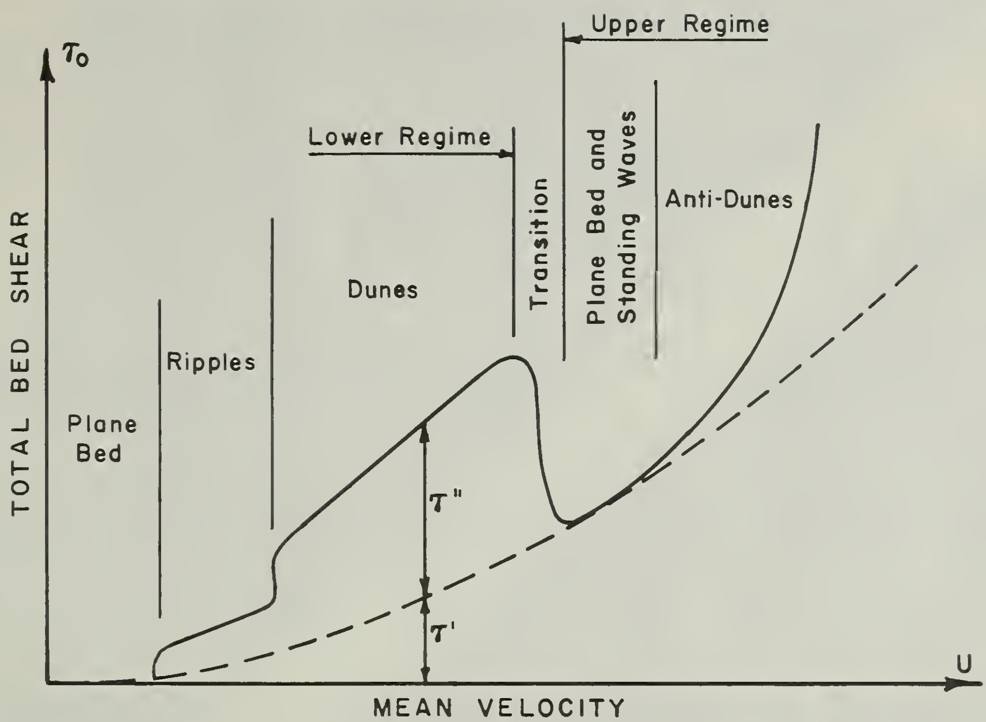


Fig. 4-3.- The Relationship between ($\tau'$) and form drag ($\tau''$) and total bed shear ($\tau_0$) (From Engelund-Hansen, 1967, p.28)

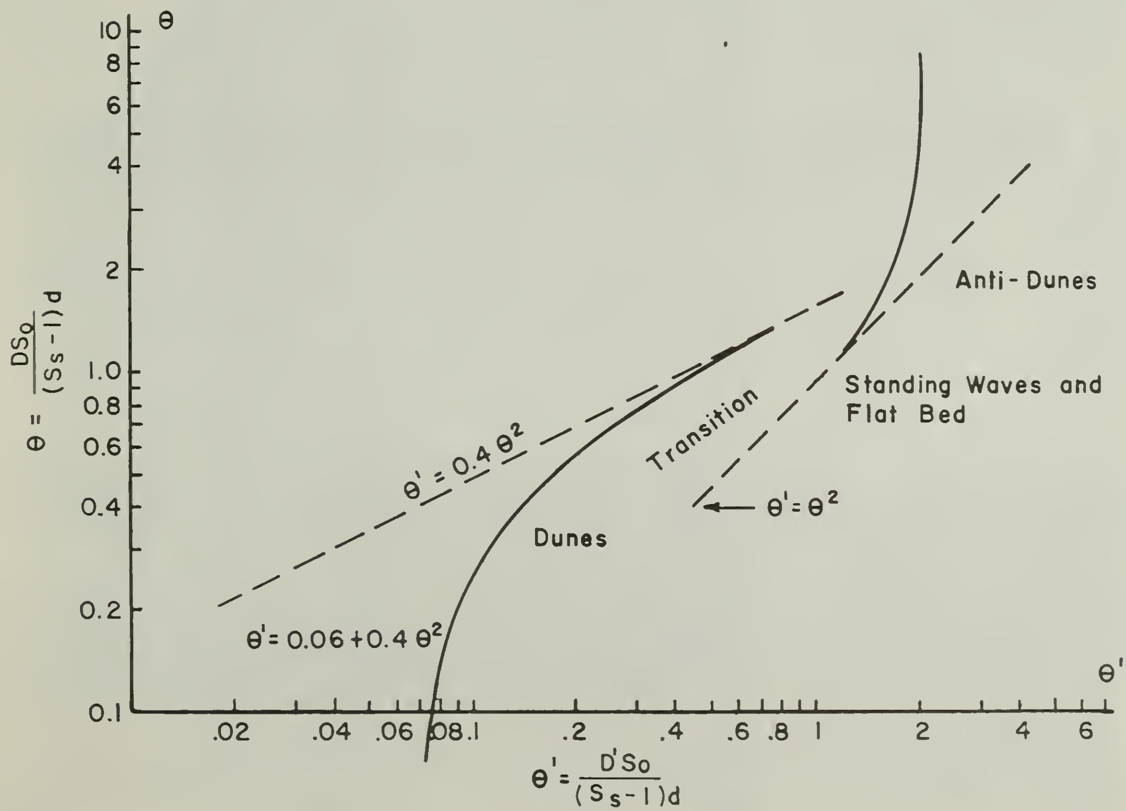


Fig 4-4.- The relationship between dimensionless forms of the bed shear ($\theta$) and ($\theta'$) (From Engelund-Hansen, 1967, p.45)

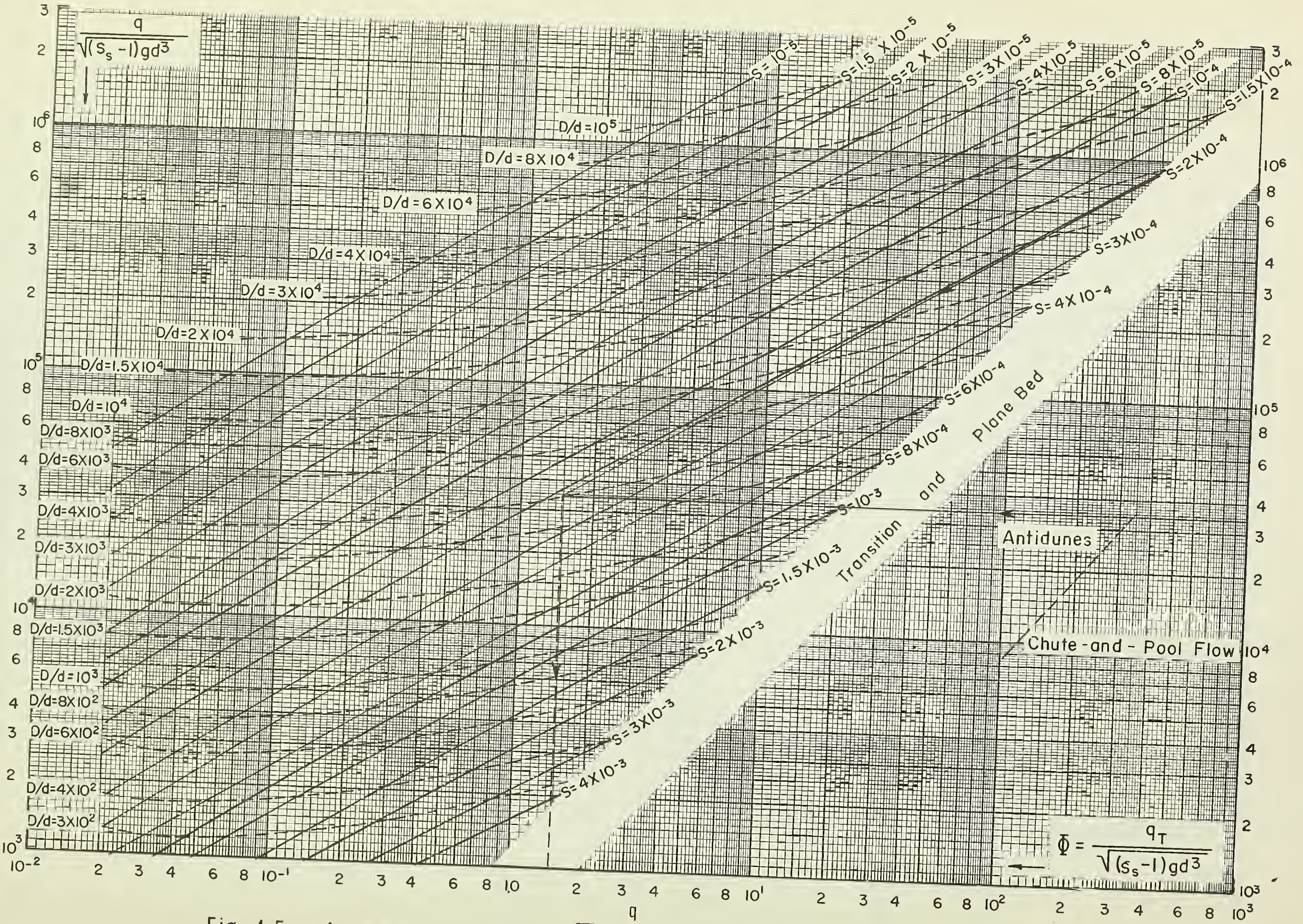


Fig. 4-5.- A graphical solution to $\frac{q}{\sqrt{(S_s-1)gd^3}}$ and $\Phi$ in the Engelund-Hansen Procedure (Adapted from Engelund-Hansen, 1967, following p. 62)

The steps in applying the graphical form are as follows, with values shown converted to metric units in order to conform with Figure 4-5.

Using the author's symbols and example:

Given: $D$ = mean depth of 4.0 feet = 1.219 meters

$d$ = mean fall diameter of $0.32 \times 10^{-3}$ meters

$S_o$ = slope of the channel = $2.17 \times 10^{-4}$

$S_s$ = specific gravity of sediment = 2.68

Calculate the ratio of the mean depth to the mean fall diameter of the bed material. The specified use of the fall diameter, defined as the diameter of a sphere having the same settling velocity in water at 24° C. results in a minor difference from sieve diameter except for coarser sand sizes.

$$\frac{D}{d} = \frac{1.219}{0.32 \times 10^{-3}} = 3.81 \times 10^3 \qquad (6a)$$

Referring to Figure 4-5, the ordinate of this point with $q = UD$ by definition:

$$\frac{q}{\sqrt{(S_s - 1)gd^3}} = 3.3 \times 10^4 \text{ and abscissa is } \Phi = 1.5 \qquad (6b)$$

In the next step, the water discharge per foot of width is determined by this procedure as an interdependent discharge, sediment transport relationship in a sand bed stream.

$$q = \sqrt{S_s - 1)gd^3} \times \text{ordinate in previous step} \qquad (6c)$$

$$= [1.68(9.8)(0.32 \times 10^{-3})^3]^{1/2} \; (3.3 \times 10^4)$$

$$= 2.33 \times 10^{-5} \; (3.3 \times 10^4) = 0.769 \text{ m}^2\text{/sec} = 8.28 \text{ cfs/ft}$$

$$q_T = \Phi \sqrt{(S_s - 1)gd^3} \qquad (6d)$$

$$q_T = 1.5 \sqrt{1.68(9.8)(0.32 \times 10^{-3})^3} = 3.50 \times 10^{-5} \text{ m}^2\text{/sec}$$

Conversion of m$^2$/sec to lb/sec ft, assuming weight of sediment as 95 lb/cu ft. Therefore 1 m$^2$/sec = $(3.28)^2(95)$ = 1022 lb/sec

$$q_T = 3.50 \times 10^{-5}(1022) = 0.036 \text{ lb/sec per ft}$$

The next example shows early in the calculations that the long form of computations will have to be substituted.

Given:

$D$ = mean depth of 1.0 foot = 0.3048 meters

$d$ = mean fall diameter of $0.32 \times 10^{-3}$ meters

$$\frac{D}{d} = \frac{0.3048}{0.32 \times 10^{-3}} = 0.952 \times 10^{3} \qquad (7a)$$

$S_s$ = 2.68

$S_o$ = slope of the channel = $2.00 \times 10^{-3}$

Referring to Figure 4-5, it is seen that the values would fall to the right of the lined chart and probably in the transition and plane bed regime.

$$\theta \text{ (see Fig. 4-3 and 4-4)} = \frac{D\ S_o}{(S_s - 1)d} = \frac{(0.3048)(0.002)}{(1.68)(0.00032)} \qquad (7b)$$

$$= 1.135$$

$\theta'$ = for transition or plane bed regime = $0.4\ \theta^2$ = 0.515 (7c)

$$D' = \text{(boundary layer thickness)} = \frac{\theta'}{\theta} D = \frac{0.515}{1.135}(0.3048) \qquad (7d)$$

$$= 0.138 \text{ m}$$

$k$ = (surface roughness, as determined by Engelund-Hansen) (7e)

= 2.5 d <u>in mm</u> = 2.5(.32) = 0.80 mm

$$\frac{U}{\sqrt{gD'S_o}} = 6.0 + 5.75 \log \frac{D'}{k} \text{ in mm} \qquad (7f)$$

$$U = [9.8(0.138)(.002)]^{1/2}\ [6.0 + 5.75 \log \left(\frac{138}{0.80}\right)] = 0.98 \text{ m/sec}$$

$U$ = 3.22 ft/sec $\therefore$ discharge = 3.22 cfs/ft

The bed material discharge may be calculated from the equation:

$f\Phi = 0.1\ \theta^{5/2}$ (as determined by Engelund-Hansen) in which

$$f \text{ (friction factor)} = \frac{2g\ S_o\ D}{U^2}$$

$$= \frac{2(9.8)(.002)(.3048)}{(0.981)^2} = .0124 \qquad (7g)$$

$$\text{and } \Phi = \frac{0.1}{f}\,\Theta^{5/2} = \frac{0.1}{.0124}\;1.135^{5/2} = 11.06 \qquad (7h)$$

$$q_T = \Phi\sqrt{(S_s - 1)gd^3} = 11.06\sqrt{1.68(9.8)(0.32 \times 10^{-3})^3} \qquad (7i)$$

$$= 2.577 \times 10^{-4} \times 1022 \text{ lb (@ 95 lb/cu ft)}$$

$$= 0.263 \text{ lb/sec per ft}$$

In summary, the velocity 3.22 ft/sec, discharge 3.22 cfs/ft of width and bed-material transport 0.263 lb/sec/foot of width are determined for a transitional or upper plane bed regime. The Engelund-Hansen procedure does not provide a means for determining the bed-material discharge at lower flow regimes of plane bed and ripples. These regimes are not significant in terms of transported sediment volumes.

<u>The Colby procedure for relating mean velocity to sand transport</u>. - The Colby procedure was developed through the correlation of mean velocity with concentration of sediment in a sand bed stream. The procedure, entirely empirical, is based on measurements in flumes and channels. The relationships are presented in four graphs. The first of these shown in Figure 4-6 gives the uncorrected sand transport as a function of velocity, depth and the $d_{50}$ particle size of bed material for water depths, D, of 0.1, 1, 10 and 100 feet, respectively. Each of the four sets contains curves corresponding to $d_{50}$ of 0.10, 0.20, 0.30, 0.40, 0.60 and 0.80 mm. Before the graphs of Figure 4-6 can be used, the velocity must be obtained by observation or calculation. The bed-material load for flows with depths other than the four values for which curves are given can be obtained by reading the sand transport per foot of width, $q_T$, for the known velocity for two of the depths indicated in Figure 4-6 which bracket the desired depth. A plotting of D versus $q_T$ on log-log paper enables an interpolation of the bed-material load for the desired depth.

The bed-material load obtained in the described manner corresponds to water temperature at 60° F. and to material with negligible amounts of fine particles such as silt and clay, in suspension. The two correction factors, $K_1$ and $K_2$, shown in Figure 4-7a account for the effect of water temperature and concentration of fine suspended sediment on the sediment discharge when the $d_{50}$ size of the bed sediment is about 0.2 to 0.3 mm. Figure 4-7b represents an estimate of the relative effect of concentration of fine sediment or of water temperature for different $d_{50}$ sizes of bed sediment than on Figure 7a. The adjustment coefficients to be read from Figure 4-7a are not to be directly multiplied by percentages in Figure 4-7b for sizes other than 0.2 to 0.3 mm; rather the adjustment coefficients minus 1.00 are to be multiplied by the percentages. For example, if an adjustment coefficient ($K_1$ or $K_2$) from the main diagram is 1.50 and $d_{50}$ size of the bed sediment is 0.50 mm, $K_3$ from Figure 4-7b is 60 percent of 0.50 or 30 percent. The final adjustment coefficient would be 1.30. The author has emphasized that rough estimates only are to be derived from Figure 4-7.

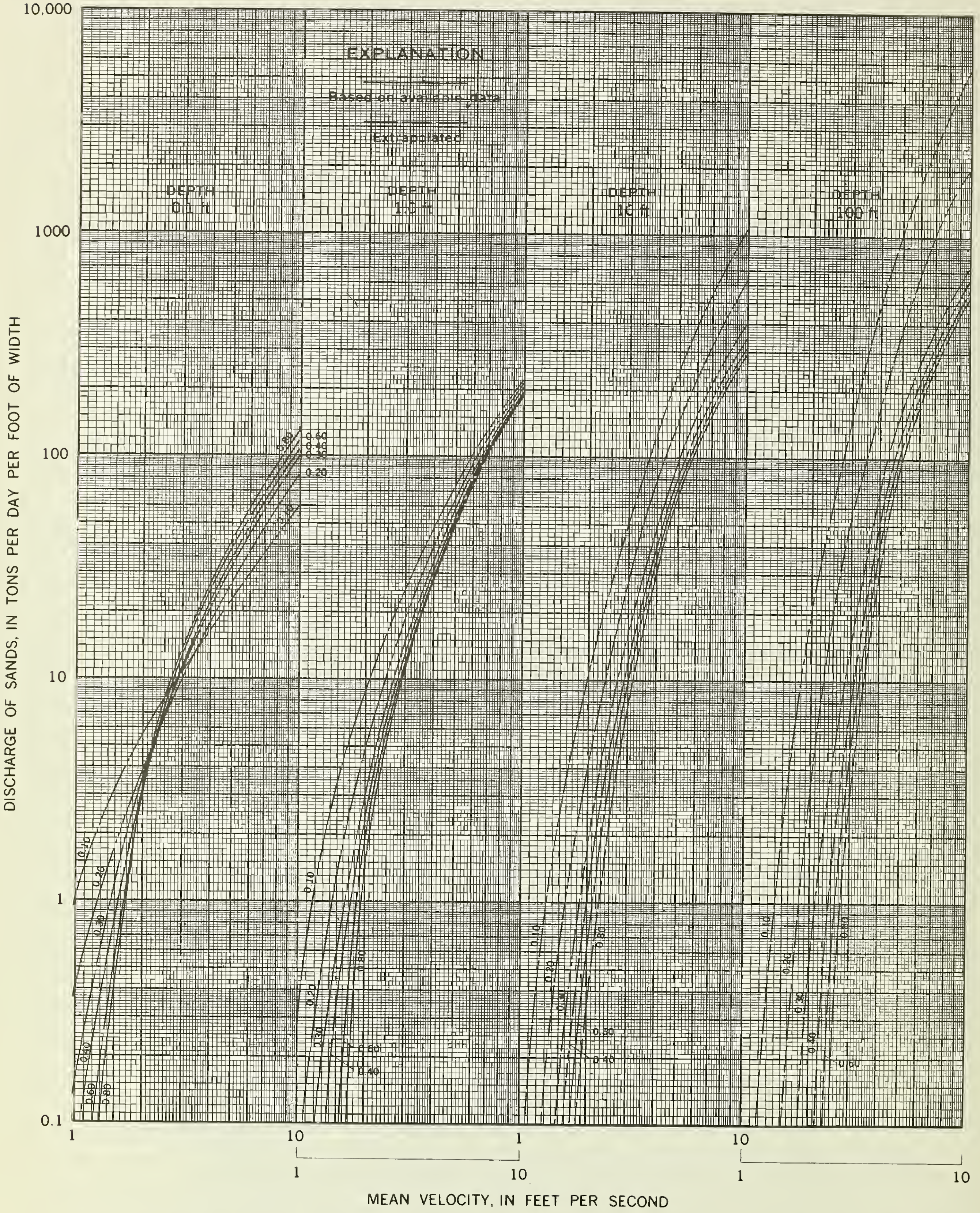


Fig. 4-6.- The relationship of discharge of sands to mean velocity for six median sizes of bed sand, four depths of flow, and a water temperature of 60°F. (From Colby, 1964, p.A 36)

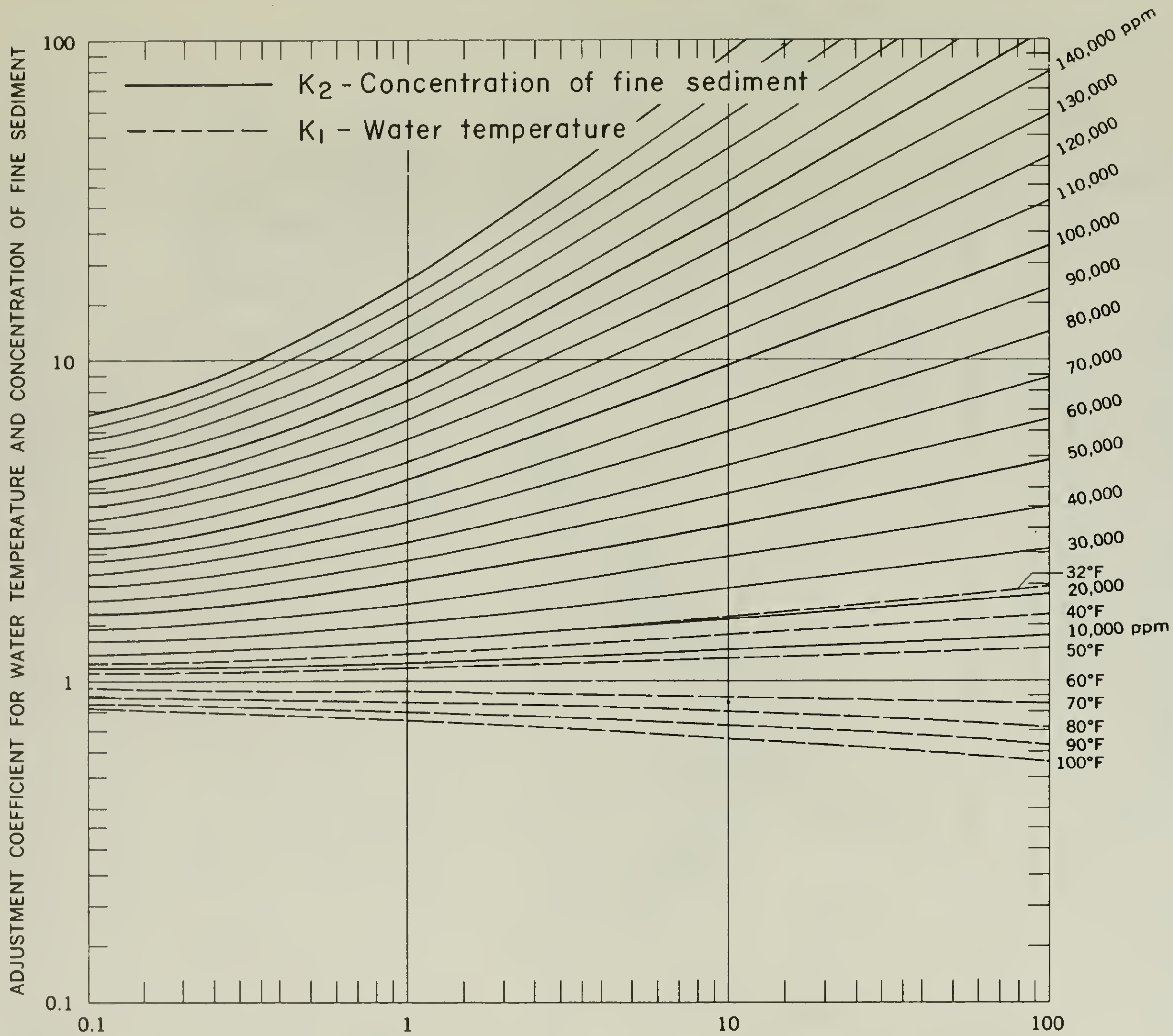


Fig. 4-7a

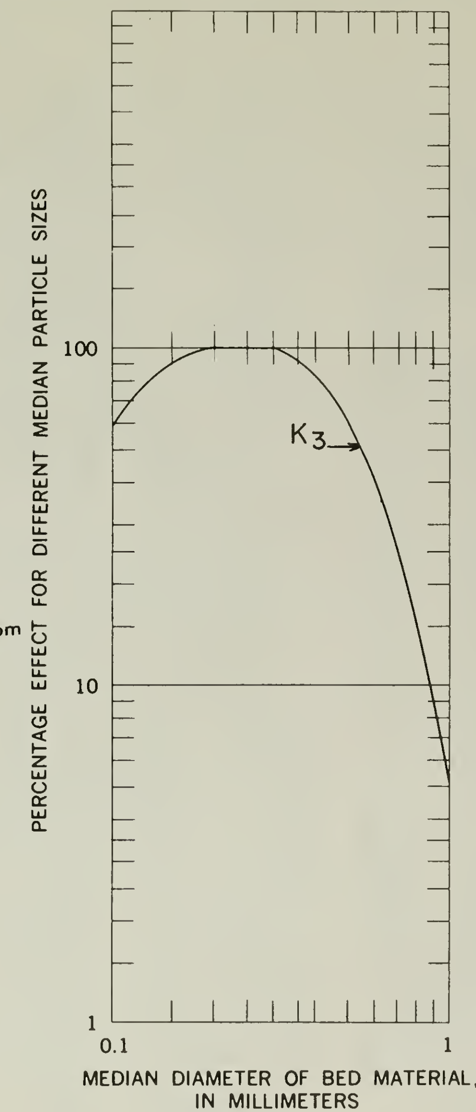


Fig. 4-7b

Fig. 4-7.- Approximate correction factors for the effect of water temperature and concentration of fine sediment (7a) and sediment size (7b) on the relationship of discharge of sands to mean velocity (From Colby, 1964, p.A31)

Determining the discharge of sands from the graphs. - - The discharge of sands in a sand bed stream can be computed from the empirical graphs as follows:

First case - Discharge of sands based on Figure 4-6

Selected data for Example 1

| | |
|---|---|
| Mean velocity | - 5.8 feet per second |
| Depth | - 8.5 feet |
| $d_{50}$ size of bed sediment | - 0.26 millimeter |

From Figure 4-6, the indicated discharges of sands for the given $d_{50}$ size are about 80 and 180 tons per day per foot for depths of 1 and 10 feet, respectively. Interpolation with a straightedge for the depth of 8.5 feet on a sheet of log-log paper indicates a sand bed material discharge of 170 tons per day per foot of width. There are no corrections required for temperature, concentration or sediment size, therefore the answer in this example is 170 tons.

Second case - Discharge of sands based on Figures 4-6 and 4-7a and 4-7b

Selected data for Example 2:

| | |
|---|---|
| Mean velocity | - 5.8 feet per second |
| Depth | - 8.5 feet |
| $d_{50}$ size of bed sediment | - 0.60 mm |
| Water temperature | - 75° F |
| Concentration of fine | - |
| bed sediment | - 20,000 ppm |

From Figure 4-6, the indicated discharges of sands are by interpolation for the given size of 0.60 mm, about 70 and 110 tons per day per foot for depths of 1 and 10 feet, respectively. Interpolation indicates a sand bed-material load of 105 tons per day per foot of width for a depth of 8.5 feet. The adjustment coefficient for temperature on Figure 4-7a, ($K_1$), is 0.85 and for a fine suspended load concentration of 20,000 ppm, ($K_2$), it is 1.55. According to Figure 4-7b, the effect of sediment size is only 40 percent as large for the diameter of 0.60 mm as for a diameter of 0.20 or 0.30 mm. Therefore, 40 percent of (1.55 - 1.00) = 0.22. The value of 0.22 is then added to 1.00 to obtain the estimated adjustment coefficient for the diameter of 0.60 mm. The 105 tons per day per foot multiplied by 0.85 and by 1.22 gives 109 tons per day per foot of width.

## Application and Limitation of Formulas

The lack of certainty in many aspects of the solution of specific sediment transport problems hinges in part on the extremely limited number of instances where predictive techniques, such as bed load or

bed-material transport formulas, have been substantiated by field measurement. Even where such substantiation is available, there is little information regarding specific hydraulic characteristics so that comparison with conditions for the problem at hand can be made.

The box diagram below illustrates a few of the major factors that may be considered in the application and limitation of sediment transport formulas. Across the top of the diagram is indicated the availability of bed material ranging from none in box A to unlimited availability of sand in the sizes less than 1 mm in box C, and increasing coarseness of bed material to gravel and boulders in box E. In the vertical two boxes are represented flow characteristics of from highly unsteady or rapidly changing flow in box 1 to steady and slowly changing flow in box 2.

Bed Material Characteristics

Sand — 0 amount to → Unlimited Sand Supply ↓ to → Coarse Gravel or Boulders ↓

Flow Characteristics: Rapidly changing (1); Steady & slowly changing (2)

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | 1A | 1B | 1C | 1D | 1E |
| 2 | 2A | 2B | 2C | 2D | 2E |

Of the possible conditions illustrated by this diagram, box 2C most nearly fits the flow and sediment characteristics used in developing the transport formulas. These characteristics also pertain specifically to the smaller streams with which the Soil Conservation Service is concerned and not to rivers where deep steady flows may transport gravel in a manner similar to sand. Through limited reaches and under high flows, shallow streams also transport gravel and boulders when a ready supply becomes available. There is frequently a transition from scour to deposition over a relatively short reach. Boxes adjacent to that identified as 2C (1C, 2B, 2D) may be considered as a "gray" area (shaded) where correct solutions to sediment transport problems may be obtained by inclusion of appropriate modifiers, such as changes in slope to match variations in discharge.

The effect of rapidly changing flow (the 1 box on the chart) on bed-load transport has been made the subject of a flume study by DeVries (1965). The mean grain size of the material used was 2.5 mm. After an equilibrium rate of transport was achieved with a constant supply of water and transport material, the water level was suddenly lowered while the other factors were kept constant. The change to a lower bed level because of scour and to a different rate of sediment transport during the transition to a new state of equilibrium was computed, using several procedures including the Meyer-Peter and Muller formula. It was concluded that on the basis of comparison of observed data the propagation and damping of a steady state is slow and that the use of steady state formulas to predict local, temporary transport for an unsteady state is questionable.

Even more recently, a flume study has been made of the effect of introducing a substantial increase (65%) in bed-material load, or non-equilibrium conditions, into a run where equilibrium flow and transport has been established (Rathbun and Guy, 1967). The median size of the sand used was about 0.30 mm. The effects were an increase in slope, a decrease in depth and an increase in rate of transport. In another run, the rate of sediment input was reduced about 50 percent of the equilibrium rate. At first the transport rate was about the same as during equilibrium flow, then with degradation of the sand bed at the upper end and the decrease in slope, the transport rate also decreased.

One distinction between equilibrium sediment transport and existing field conditions in the application of bed load or bed-material transport formulas is the impact of local changes in hydraulic conditions such as channel shape or width on the rate of transport or the change in available load due to a dam upstream. It has been observed that aggradation occurs in some channels even though hydraulic computations indicate that competence levels to transport sediment are exceeded at all stages of the flow. In some instances it is not known whether the aggradation has occurred in the rising or falling stage of the hydrograph. A part of the unpredicted changes can be explained by variable bed roughness not taken into account in conventional hydraulic computations. This does not necessarily explain all of the problem factors involved in predicting influences of hydraulic change on sediment transport since some of the procedures are intended to take into account the changes in bed roughness with various flows.

One of the most important requirements for use of the computational procedures is that the supply of bed material is such that the capacity for transport under existing hydraulic conditions is just satisfied, that is, neither an underload resulting in scour, nor an overload resulting in aggradation. As viewed in the field, a sand bed satisfies the necessary requirements for use of bed load or bed-material transport formulas and from the standpoint of bed material availability if the bottom is floored with sand from bank to bank and through the reach.

In considering the availability of bed materials, distinctions have been made between channels with sand and gravel beds as a result of field and laboratory studies (Kellerhals, 1966). The opinion expressed, based on these studies, is that gravel beds cannot be expected to obey the same laws as channels with sand beds. The segregation and more rapid movement of finer grains is pointed out as one of the distinctions. Another distinction between sand and gravel beds is that ripple and dune formation become less significant in gravel channels.

In nature and in terms of particle size, there is a relatively sharp division between predominantly sand and predominantly gravel bed streams. The scarcity of particles in the 2-4 mm size has been described (Sundborg, 1956, p. 191) and this scarcity is substantiated by survey of data on bed-material sizes in various parts of the United States. Material of gravel size when present in the bed therefore provides a clear distinction from sand in influencing the availability of sediment for transport and in the formation of armor.

The segregation of particles in a mixture of sizes including gravel, and the depth of scour before formation of armor has been the subject of flume studies (Harrison, 1950). The purpose was to determine the most critical condition for segregation and the building of an armor during degradation. The Einstein bed-load function was used to calculate the limiting grain diameter with equilibrium flow. The experiments determined that the value of $\Psi$ (a dimensionless parameter of transport capability) in excess of 27 is indicative of negligible transport of bed material.

The representative grain roughness $k_s$ (assumed to be $d_{65}$ in the procedures cited in the paragraph above) was found by Harrison to increase in the process of segregation and armor formation. Kellerhals has computed the $k_s$ values after armor formation to be at the $d_{90}$ sizes on the basis of data from field and laboratory studies (Kellerhals, 1966, p. 20).

On the basis of the above considerations one may suggest the following treatment of the sediment problem in streams according to conditions reflected on the chart (page 4-25).

1A, 2A - Cohesive soil, cemented gravels, rock. The initiation of movement is the important factor in channel scour or bank erosion. Critical tractive force is related to the $d_{75}$ of discrete particles. The undisturbed cohesive soil material exhibits resistance to erosion that may be due to one or several characteristics, such as structure, consolidation, cementation, or cohesion. The influence of each of these characteristics has not been identified. Their cumulative effect on erosion resistance may be determined by shear strength tests of the undisturbed soil that has been saturated to duplicate moisture conditions during channel flow (Flaxman, 1963.)

1B, 2B - A bed only partially covered with sand and exposing different material (cohesive soil, rock, etc.) as the fixed channel lining. This indicates a limited supply at this specific location. Application of sediment transport formulas will normally result in computed rates in excess of the actual amount. The potential for bank erosion should be tested by tractive force theory if the bank is composed of noncohesive materials, otherwise by the procedures dealing with cohesive soils.

2C - The sand covered bed is the condition pertinent to sediment transport formulas if the problem to be solved requires (a) an estimation of bed-material sediment transport volume during a specific interval of time and levels of discharge, (b) a comparison of bed-material transport in a reach with that in another where changes in slope, cross section or discharge may influence the design of a channel.

2D - The problems of transport of sand-gravel mixtures pertain to the potential volumes of material to be produced or to the potential for scour or aggradation. The probable depth of scour may be estimated by determining whether the maximum tractive force for a given flow will exceed the critical for the coarsest 5 to 10 percent of the bed material. If the maximum tractive force does exceed the critical for the $d_{90}$ - $d_{95}$, the depth of scour is not predictable except in the case where still coarser material underlies bed surface material. The amount of scour necessary to develop the armor formed of the coarsest fraction can be determined by both the depth of scour and the volume of material removed in reaching this depth.

1D, 1E, 2E - Gravel and gravel-boulder mixtures. The determination of depth of scour and volume of material produced by scour is similar to 2D. The application of bed-load formulas to this type of material is not recommended except when confined flow and steepness of slope with uniformity of cross section are conducive to relatively uniform discharge per foot of width. The highly variable velocity and discharge per foot of width in many alluvial channels is particularly conducive to alternating deposition and scour of coarse bed material.

The possibilities of bed-material transport at or approaching a constant and predictable rate exclude delivery in the form of slurries, or other forms which change the viscosity and natural sorting processes of flow. Typical of the setting for viscous flow are the alluvial fills of mountain or foothill canyons. Exceptional storm runoff following an accumulation of many years may produce debris or mud flows whose volume can be predicted only by field measurement.

## Comparison of Predictive Methods

Figures 4-8 to 4-10 show a comparison of measured bed-material sediment transport with computed rates by a number of formulas except for the Colorado River at Taylor's Ferry where the total bed-material discharge was obtained from suspended sediment samples by the modified Einstein method (Sedimentation Sec., USBR, 1958). The method of presentation was adapted from a published report (Vanoni, Brooks and Kennedy, 1961).

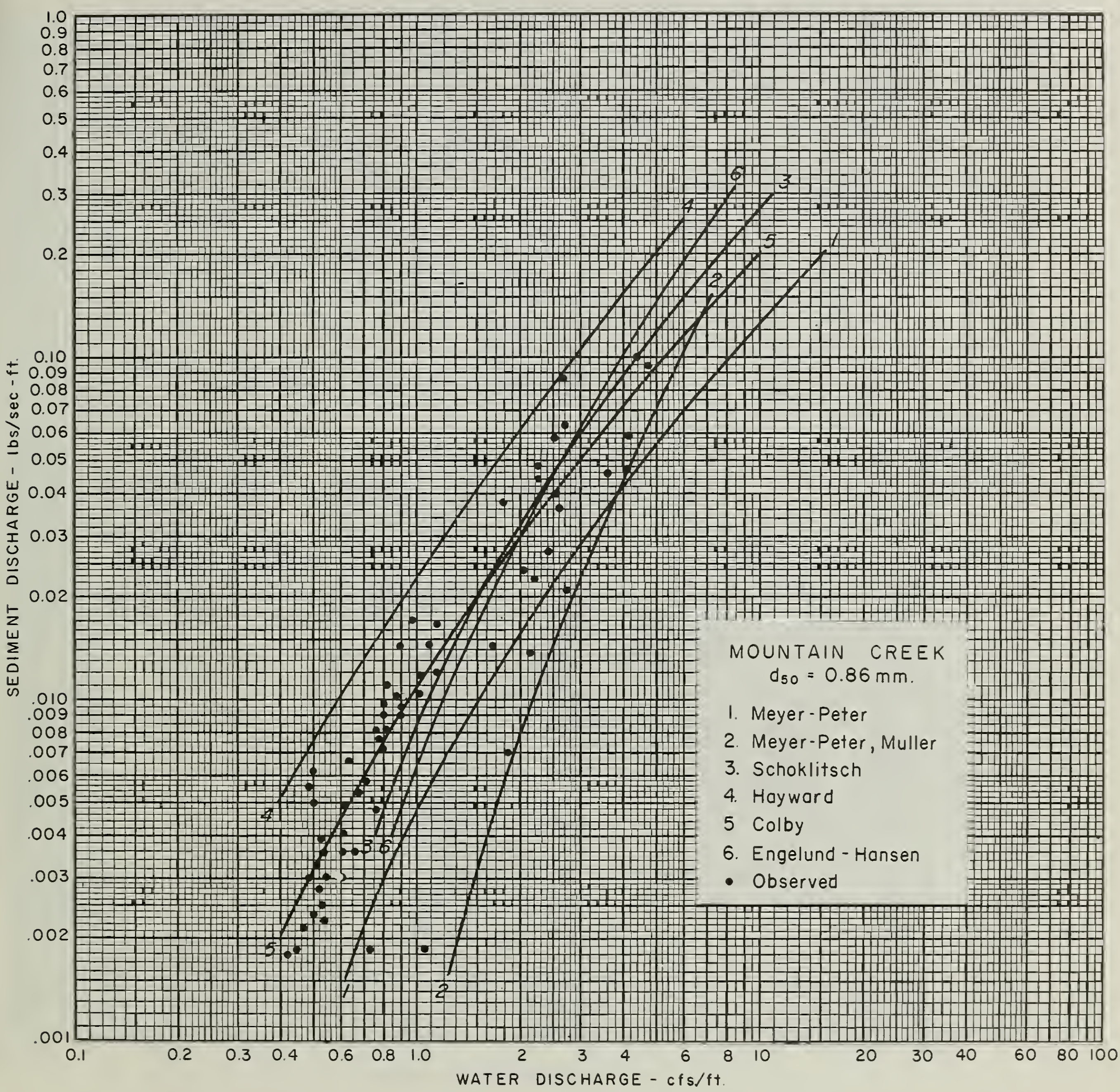


Fig. 4-8.- Sediment rating curves for Mountain Creek near Greenville, South Carolina according to several formulas compared with measurements. (Adapted from Vanoni, Brooks, and Kennedy, p.7-8)

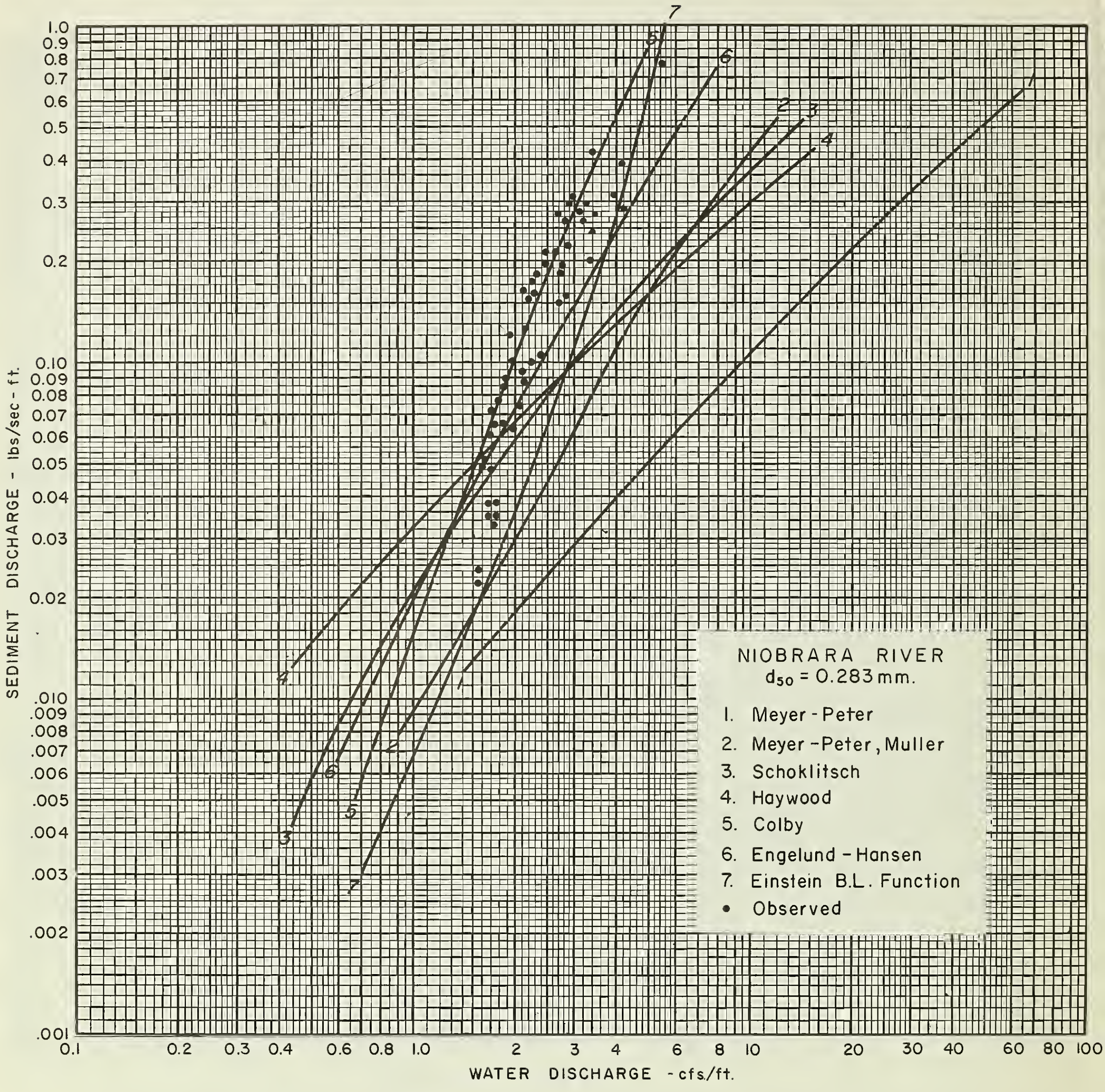


Fig. 4-9.- Sediment rating curves for Niobrara River near Cody, Nebraska according to several formulas compared with measurements (Adapted from Vanoni, Brooks, and Kennedy, 1961, p.7-5)

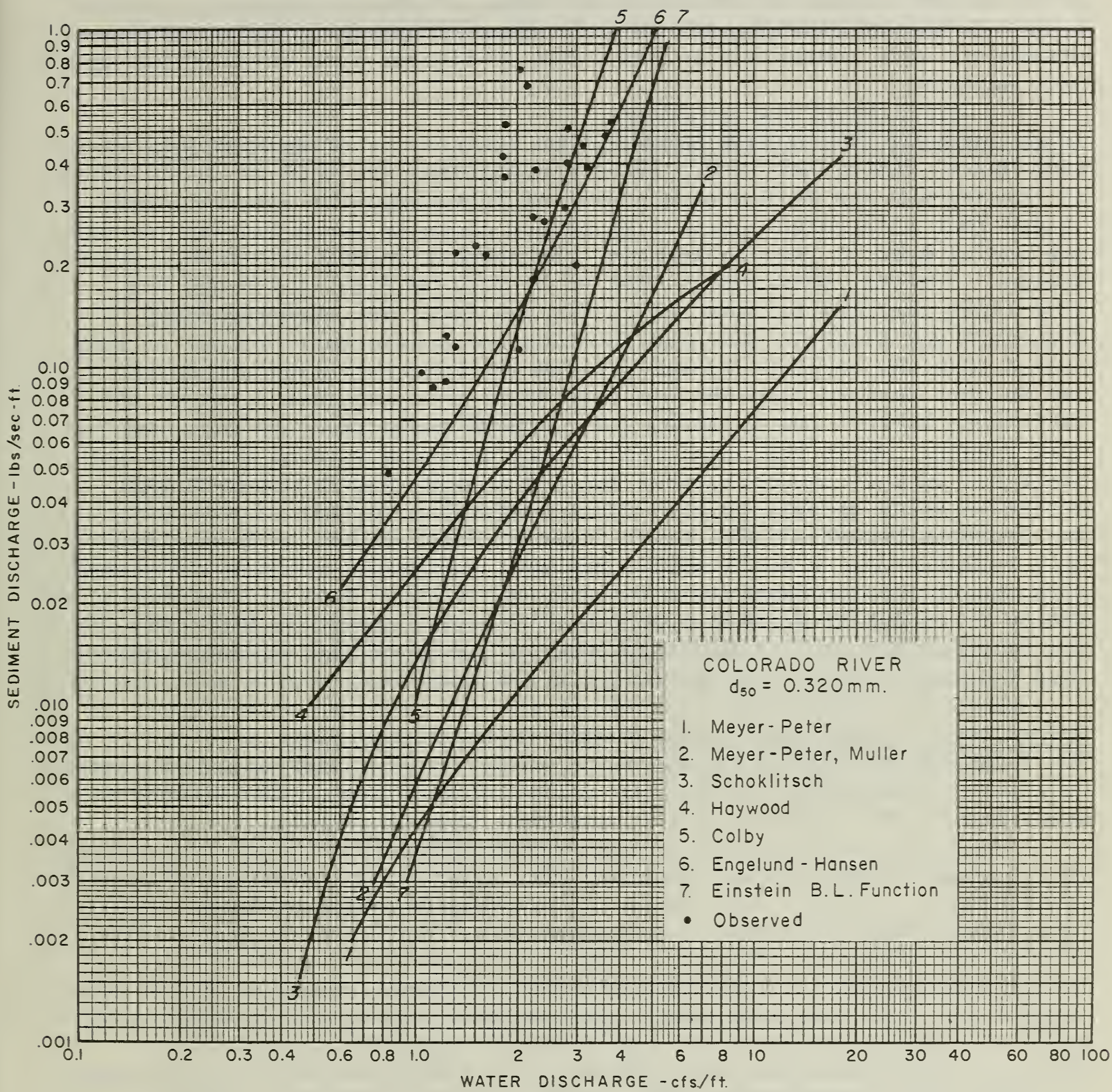


Fig. 4-10.- Sediment rating curves for Colorado River at Taylors Ferry, Arizona according to several formulas compared with measurements (Adapted from Vanoni, Brooks, and Kennedy, 1961, p.7-6)

Figure 4-8 indicates that the rates of bed-material transport in Mountain Creek as derived by formulas more closely follow the general trend of measurements than on the Niobrara and Colorado rivers, Figures 4-9 and 4-10. It may be that the stream and transport characteristics on this stream are more comparable to the flume conditions from which most formulas were derived.

In an analysis by the Task Committee on preparation of an ASCE Sedimentation Manual (ASCE, Sed. Man., 1969) a comparison was made of measurements on Figures 4-9 and 4-10 with a number of formulas. The committee concluded that calculated curves with slopes close to those fitting the data are useful even if they do not give the correct values of sediment discharge. Further, they stated that no formula on Figures 4-9 and 4-10 give lines parallel to those which fit the data, but that the Colby procedure and Einstein Bed-Load Function are consistently better in this regard than the others. It was pointed out that the Colby procedure was in part derived from the Niobrara River data and that a better relationship between the measured and computed rates could be expected for this reason. While the committee's study included several formulas not described in this handbook, they did not include the Engelund-Hansen procedure which appears to have merit comparable to that of the Colby and Einstein methods. (The Meyer-Peter or Meyer-Peter and Muller bed-load formulas may be applicable for gravel and gravel-boulder mixtures with the limitations explained in paragraph 4, page 4-28.) The committee's conclusion is that appropriate formulas should be used only for relating transport capability between one reach and another rather than for obtaining dependable quantitative results.

Comparison as demonstrated by a channel stability problem

The following example is illustrative of the similarities and differences in results that may be obtained by application of two of the procedures described in this section of the handbook.

An existing channel 20 feet wide and with a bed slope of 0.002 ft/ft has an inadequate capacity for control of flooding of adjacent lands. It is proposed that the width of this channel be increased to 30 feet to provide the necessary capacity. Field investigations have shown that an unlimited supply of sand is available for transport in the bed of the channel and that this sand has a $d_{50}$ size of 0.30 mm. Given the hydrograph of a specified (possibly the design) frequency, the problem to be solved is whether the improved reach of channel, with the only change being the increase in width, will remain stable, degrade or aggrade. For purposes of simplification it is assumed that the banks will have no influence on depth-discharge relationships. In point of fact, however, roughness of the banks and differences in roughness of banks in the unimproved and improved reaches can affect depth and velocity for a given discharge and thereby the rate of bed-material transport. The hydraulics of the flow, which includes a distribution of shear on the banks as well as the bed, must be made by an established procedure, as in TR-25, prior to the bed-material transport computations.

The hydrograph to be used in this example is broken into several segments for the purpose of determining the discharge per foot of stream width as required for the computational procedures. The mean discharge and duration for each of the hydrograph segments are as follows:

| | Discharge per ft of width | |
|---|---|---|
| Rising stage | 20' channel (cfs) | 30' channel (cfs) |
| a. Mean flow for 2 hours - 90 cfs | 4.5 | 3.0 |
| b. Mean flow for 2 hours - 280 cfs | 14.0 | 9.3 |
| Falling stage | | |
| c. Mean flow for 3 hours - 240 cfs | 12.0 | 7.5 |
| d. Mean flow for 3 hours - 180 cfs | 9.0 | 6.0 |
| e. Mean flow for 3 hours - 40 cfs | 2.0 | 1.3 |

Two procedures are used in this problem. These are the Schoklitsch formula and the Colby procedure. For use of the Schoklitsch formula the only discharge data required is the amount of discharge per foot of width. The Colby procedure requires velocity and depth of low. To determine velocity and depth for a given discharge (unless they are available from stream-gage records) it is necessary to either assume an "n" roughness coefficient for use in the Manning equation or obtain such values from empirical data. To enable solution of the problem in the example by the Colby procedure, two approaches were used. In one, a constant assumed "n" of 0.020 was used and in the other, the most recent and perhaps the most reliable procedure for predicting friction factors and thereby the depth, velocity, discharge relationships was used (Alam and Kennedy, 1969) (See appendix to this chapter).

Table 4-1 shows the results of the sediment transport computations.

This analysis indicates that in the stated problem the Schoklitsch formula and the Colby procedure give about the same results.

The next step in the analysis is to determine whether lower flows would give the same or different results. In this instance, 20 percent of the discharges on the above tabulation are used.

TABLE 4-1 Comparison of sediment transport rates with flows given on page 4-33

| | Schoklitsch | | Colby n = .020 | | Colby using Alam-Kennedy Friction Factors | |
|---|---|---|---|---|---|---|
| Discharge Segment | 20' width lbs. | 30' width lbs. | 20' width lbs. | 30' width lbs. | 20' width lbs. | 30' width lbs. |
| a | 142,500 | 145,000 | 99,400 | 95,000 | 100,100 | 79,000 |
| b | 452,000 | 500,000 | 358,000 | 342,000 | 370,000 | 400,000 |
| c | 581,000 | 554,000 | 441,500 | 410,000 | 486,000 | 500,000 |
| d | 435,500 | 435,000 | 350,000 | 335,000 | 400,000 | 388,000 |
| e | 97,200 | 94,000 | 56,100 | 55,000 | 34,600 | 25,000 |
| Totals | 1,708,200 | 1,728,000 | 1,305,000 | 1,237,000 | 1,390,700 | 1,392,000 |

| Rising stage | Discharge per ft of width 20' channel (cfs) | 30' channel (cfs) |
|---|---|---|
| a. Mean flow for 2 hours - 18 cfs | 0.9 | 0.6 |
| b. Mean flow for 2 hours - 56 cfs | 2.8 | 1.9 |
| **Falling stage** | | |
| c. Mean flow for 3 hours - 48 cfs | 2.4 | 1.6 |
| d. Mean flow for 3 hours - 36 cfs | 1.8 | 1.2 |
| e. Mean flow for 3 hours - 8 cfs | 0.4 | 0.3 |

Table 4-2 below gives the results of computing sediment transport by the same means as in the first example.

TABLE 4-2 Comparison of sediment transport rates with flows given above

| | Schoklitsch | | Colby | | Colby using Alam-Kennedy friction factors | |
|---|---|---|---|---|---|---|
| Discharge Segment | 20' width lbs. | 30' width lbs. | 20' width lbs. | 30' width lbs. | 20' width lbs. | 30' width lbs. |
| a | 9,090 | 8,940 | 6,340 | 6,500 | 2,440 | 200 |
| b | 28,700 | 29,400 | 47,000 | 46,500 | 40,000 | 31,600 |
| c | 37,000 | 36,600 | 57,600 | 58,400 | 50,200 | 34,500 |
| d | 27,500 | 27,200 | 32,200 | 26,400 | 30,000 | 13,200 |
| e | 5,700 | 5,650 | 3,450 | Neg. | Neg. | Neg. |
| Totals | 107,990 | 107,790 | 146,590 | 137,800 | 122,640 | 79,500 |

Examination of Table 4-2 indicates that there is little relative difference between the results using the Schoklitsch formula and the Colby procedure with a uniform "n" value; however, there is a substantial difference in results between these and the Colby procedure using the Alam-Kennedy method of determining friction factors. It is believed that the latter more closely reflects the influence of variable bed forms during low to moderate flows.

The above study indicates that any one of several formulas may be used for determination of relative rates of bed-material transport when variation in bed forms may not be a factor. This could pertain to channel performance at peak discharges. However, in many stability problems the performance of the channel during one or a series of frequent low to moderate flows must be considered. Greater flexibility for all purposes is offered by use of those formulas and procedures which enable determination of the effect of variable bed forms on depth, velocity and discharge relationships and thereby on bed-material discharge.

## Summary of Procedures for Evaluation of Bed-Material Transport Problems

Problems involving bed-material transport require, as steps toward their solution, consideration of three elements. These are (1) the nature of the existing problem, (2) the availability of bed material, and (3) the influence of natural or artificial changes in stream or watershed conditions. The nature of the existing problem can best be determined by field investigation and analysis. Surveys of old and new cross sections, application of techniques for identifying depths of scour or aggradation, comparison of aerial photography, all facilitate the identification of a problem.

While the correct identification and analysis of existing bed-material transport conditions is important, the majority of problems revolve around the need for projecting what will or can occur rather than what is occurring. Consideration of the availability of bed material and the impact of change are the key elements of such projections.

It has been stated above that equilibrium conditions can only be achieved when a supply of bed material is available in the bed and an amount is being introduced into the reach at a rate comparable to its movement out of the reach. Problems arise when the amount introduced exceeds or is less than the transport capacity of the flow. In other words, equilibrium transport creates few, if any, problems, but a change from equilibrium to nonequilibrium transport can do so.

A supply of bed material in excess of downstream transport capability can occur during exceptional discharges. This may be due to development of new and substantial sources of bed material within or adjacent to the problem reach and by channel changes which may increase transport capacity in the upstream reach but not in the downstream reach. Determination of the availability of bed material is largely a field problem. To be readily available to channel flow, sediment of specified bed-material size must be in the stream system and movable in correspondence with variation in discharge. The coarser particles in an upland soil profile, which usually constitute bed material, tend to lag behind in the erosion process. Gullies that feed directly into the stream system and that are exposing soils with a high percentage of bed-material sizes can be major contributors but do not in themselves constitute an immediate and unlimited stream channel supply.

Stream banks which consist, at least in part, of soil textures comparable to those in the bed, may provide a ready source of supply depending upon the ease with which the flow can erode the material. An emergency flood protection measure frequently used is to bulldoze bed materials which have aggraded a stream to each side to form banks or levees. These banks form a ready source of supply and their erosion and consequent deterioration of channel alignment results in overloading of the flow and aggradation.

Scour of bed material results from the entrance of underloaded flow into an alluvial reach. Upstream changes in watershed or stream conditions that may reduce the supply of incoming bed material include the removal of supply by major flood scour, construction of reservoirs, debris basins or other structures.

In addition to cutting off the supply of bed material to the adjacent reach downstream, a reservoir may otherwise materially influence the stability of the channel bed and banks by modification of the flow. For example, a detention structure that effectively controls a high flood peak may thereby extend the duration of released flows that exceed the critical tractive force for channel boundary materials by days. The resulting bed and bank scour may be extensive.

Table 4-3 is a checklist of procedures to be considered for the solution of bed-material transport problems. The last column on this table indicates that a field evaluation is important to the solution of any such problem. The variety of factors that may influence the solution of problems indicates that most of them are other than of a routine nature and that they require the involvement of well trained and experienced personnel. In all instances, the first step should be a field interpretation of existing or potential problems related to sediment transport. With experience, questions of stability, degradation or aggradation can frequently be answered by relating the availability of bed material to proposed changes in hydraulics of the flow without resort to formulas. When necessary to employ the latter, it should be with the recognition that the results are qualitatively and not quantitatively useable.

## Suspended Sediment-Load Transport

Suspended sediment load includes both the bed-material load in suspension and the wash load, as shown on Figure 4-2, page 4-12. Where the erosion of fine-textured soils is the chief source of sediment, the wash load rather than the total bed-material load usually constitutes the majority of the sediment discharge. No method exists to predict rates of wash-load transport without a substantial amount of data on suspended sediment concentrations during measured discharges.

TABLE 4-3 Checklist of procedures for solution of bed-material transport problems

| Problem Characteristics | Analysis Procedures: Tractive Stress 1/ | Comparative Hydraulics 2/ | Bed Material Formulas | Field Evaluation |
|---|---|---|---|---|
| **Sediment Problem** | | | | |
| Erodibility of bed | x | | | x |
| Erodibility of bed and banks | x | | | x |
| Erodibility of banks | x | | | x |
| Channel aggradation | | x | x | x |
| Volume of bed material | | | x | x |
| Effects of channel change | | x | x | x |
| **Channel Boundary Characteristics** | | | | |
| Cohesive soils | x | | | x |
| Cohesive soils or rock with intermittent deposits of sand or gravel | x | | | x |
| Sand $\lesssim$ 1.0 mm | x | x | x | x |
| Sand $\lesssim$ 1.00 mm with < 10% gravel | x | x | x | x |
| Gravel, gravel mixed with sand | x | | 3/ | x |
| Gravel and boulders | x | | 3/ | x |
| **Hydraulic Characteristics** | | | | |
| a. In problem reach | | | | |
| Steady state or slowly changing | x | x | x | x |
| Rapidly changing | x | x | | x |
| b. Cross section - slope upstream vs. problem reach | | | | |
| About the same | x | x | x | x |
| Steeper slope | x | x | x | x |
| Wider channel | x | x | x | x |
| Narrower channel | x | x | x | x |

1/ For cohesive soil boundaries, analysis may include tractive power, or tractive stress times mean velocity.

2/ Comparison of depth-velocity-unit discharge relationships in two or more reaches.

3/ Special situations, see page 4-28.

The suspension mechanism

A report of the Subcommittee on Sedimentation, Inter-Agency Committee on Water Resources, presents a clear, brief description of a theory of suspended sediment load. A statement from this report is quoted directly (Subcom. Sediment Inter-Agency Comm. on Water Resources, Report No. 14, December 1963, p. 26).

> Sediment carried in suspension (which includes both bed material in suspension and wash load) is acted on in the vertical direction by momentary currents which move upward or downward in the stream. Because the water level in the stream remains unchanged, the quantity of upward and downward flow must be equal. If the upward and downward currents were the only forces affecting the vertical movement of sediment, complete mixing would soon take place and the concentration of sediment would become uniform throughout the depth. However, all particles of specific gravity greater than that of water settle steadily downward. Under the combined action of vertical currents and gravitational force, a particle caught in a current moving upward at a rate greater than the settling velocity of the particle should be transported upward, but if it is suspended in water moving downward, or moving upward at a rate less than its settling velocity, the particle should move downward. It might seem that the downward currents would take down as much sediment as the upward ones carry up, with the result that all the material finally would settle to the bottom. However, as settling takes place the sediment concentration increases toward the bottom, and the upward currents travel from a region of higher concentration to one of lower concentration, whereas for the downward currents the opposite relationship prevails. As the amounts of water moving upward and downward are equal and the sediment concentration in the rising currents is potentially greater than in the downward currents, more sediment must be acted upon by the rising than by the falling currents. The settling action superimposed on the fluctuating upward and downward currents tends to produce a balanced suspension in which the rate of increase in sediment concentration toward the bottom depends upon the degree of turbulence in the stream and the settling velocity of the suspended particles.

For sediment particles of uniform density, the settling rate increases with size, but not proportionally. The settling rate for particles smaller than about 0.062 mm in size varies approximately as the square of the particle diameter, whereas particles of coarse sand settle at rates which vary approximately as the square root of the diameter. Particles of intermediate size have settling velocities which vary at intermediate rates. The 0.062 mm size approaches the division point between sediments classed as silts and those classed as sands. Clay particles (which are finer than silts) and silt particles are ordinarily fairly uniformly distributed in a stream, but sand particles are

usually more concentrated near the bottom than near the surface, the degree of variation being a function of the coarseness of the particle (Figure 4-11).

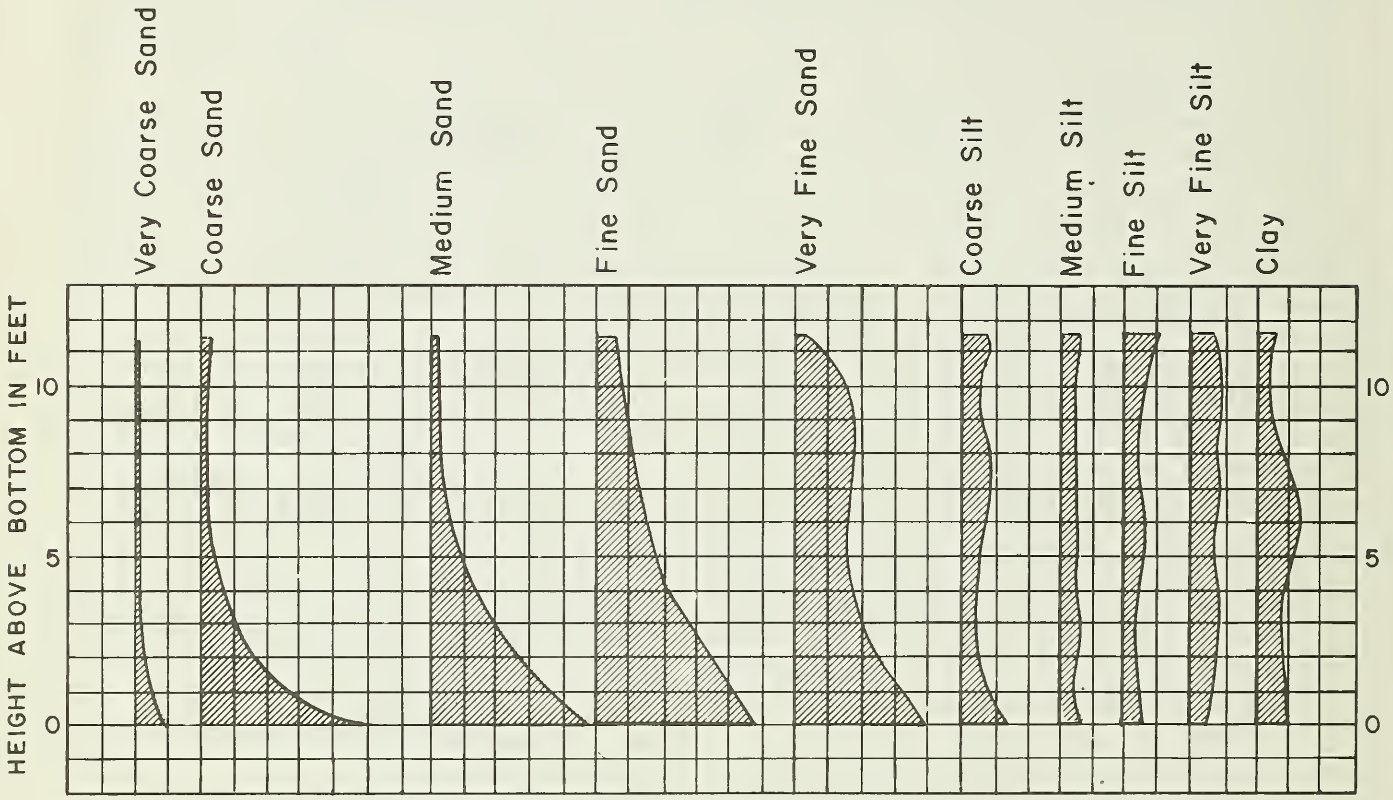


Fig. 4-11.- Vertical distribution of sediment in Missouri River at Kansas City, Mo.(From Subcommittee on Sedimentation, Inter Agency Committee on Water Resources, Report N 14, December, 1963,p.28)

The lateral distribution of suspended sediment across a stream is fairly uniform for either deep or shallow flows. The exception is below the junction of a tributary carrying material at a substantially different concentration than the main stream. The flow from the tributary tends to stay on the entrance side of the channel for some distance downstream.

Sampling and laboratory procedures

The U. S. Geological Survey obtains most of the suspended sediment load samples collected in this country. They generally use integrating samplers developed by the cooperative project of the Subcommittee on Sedimentation, Inter-Agency Committee on Water Resources. The integrating sampler is lowered and raised vertically in the flow at a uniform rate. Travel time to and from the bed is regulated for a return to the

surface with the container not quite full of the water-sediment mixture. This procedure provides uniform sampling for the depth of the flow. Flows are sampled to within about 4 inches of the bed, which is approximately the vertical distance between the intake nozzle and the base of the instrument.

Point integrating samplers are provided with a tripping mechanism that enables sampling at any point in the flow. Data on concentrations of bed material obtained by this equipment and composition of the bed material are used in total bed-material load computations. The point-integrating sampler is sometimes used in streams too deep for equipment limited to obtaining integrated samples only. The latter can sample only from the surface to a maximum depth of about 16 feet.

Laboratory procedures used in handling the samples include weighing the container holding the water-sediment mixture, then decanting clear liquid, evaporating the remaining moisture and weighing of the dry sediment. The ratio of the dry weight of the sediment times 1,000,000 to the weight of the water-sediment mixture is the sediment concentration in parts per million. Expressing the suspended-sediment concentration in milligrams per liter has become common useage recently because of the metric system being adopted by most countries. The following formula may be used for this purpose (A.S.C.E. Proc. No. 6757 HY5, 1969, p. 1517).

$$\text{Concentration in mg per l} = A\,\frac{\text{weight of sediment} \times 1{,}000{,}000}{\text{wt of water-sediment mixture}} \qquad (8)$$

in which the Factor A is given in Table 4-4.

TABLE 4-4. Factor A for computation of sediment in milligrams per liter in the formula (8)

| Ratio $\frac{\text{weight of sediment}}{\text{wt of sediment \& water}} \times 10^6$ | A | Ratio $\frac{\text{weight of sediment}}{\text{wt of sediment \& water}} \times 10^6$ | A |
|---|---|---|---|
| 0 - 15,900 | 1.00 | 322,000 - 341,000 | 1.26 |
| 16,000 - 46,900 | 1.02 | 342,000 - 361,000 | 1.28 |
| 47,000 - 76,900 | 1.04 | 362,000 - 380,000 | 1.30 |
| 77,000 - 105,000 | 1.06 | 381,000 - 398,000 | 1.32 |
| 106,000 - 132,000 | 1.08 | 399,000 - 416,000 | 1.34 |
| 133,000 - 159,000 | 1.10 | 417,000 - 434,000 | 1.36 |
| 160,000 - 184,000 | 1.12 | 435,000 - 451,000 | 1.38 |
| 185,000 - 209,000 | 1.14 | 452,000 - 467,000 | 1.40 |
| 210,000 - 233,000 | 1.16 | 468,000 - 483,000 | 1.42 |
| 234,000 - 256,000 | 1.18 | 484,000 - 498,000 | 1.44 |
| 257,000 - 279,000 | 1.20 | 499,000 - 513,000 | 1.46 |
| 280,000 - 300,000 | 1.22 | 514,000 - 528,000 | 1.48 |
| 301,000 - 321,000 | 1.24 | 529,000 - 542,000 | 1.50 |

There are two classes of suspended sediment load stations, daily and periodic. Stations reporting on a daily basis may include an average of several or more samples during high or variable discharge. Periodic stations include those where samples are obtained about every two weeks or less often. Reporting on daily stations shows the mean discharge, sediment concentration, tons and a summation of the latter for the month and year. Periodic stations usually show the data for the day of sampling only. The size distribution is frequently available for representative samples.

With daily or more frequent data on suspended sediment load concentrations available, tons per day may be computed by plotting concentrations directly on a chart showing the gage height against time. A smooth curve is then drawn through the plotted points and daily mean concentrations are read from the graph. When data on rapidly changing concentrations and water discharge are available, the graphs are divided into smaller increments of time (ASCE Proc. No. 6756 HY5, 1969, p. 1506).

Sediment rating curve-flow duration curve method of computing suspended sediment load

Periodic or short time daily suspended sediment load data are sometimes extended for more meaningful use as average annual yields by construction of sediment rating and flow duration curves (Miller, 1951). An example of a sediment rating curve is shown in Figure 4-12. It is constructed by plotting discharge and sediment load data in tons on log-log paper. It is not essential that all data available be used in such a plot, but enough for a wide range of discharges enabling drawing a curve that will cover and perhaps extend the range of experienced relationships between the two sets of data.

To construct a flow duration curve, data on mean discharges are divided into a series of classes with a range which the records indicate the stream at this station has experienced. Then the number of days occurring within each class for the period of record are counted. The percent of time falling within each class is determined and the midpoint is plotted on log-probability paper relative to the accumulated percentage at that point. Figure 4-13 is an example of a flow duration curve. Table 4-5 is an illustration of how the sediment rating curve and the flow duration curve are used to determine the annual sediment yield for the period on which the flow duration curve is based. Construction of the curve in this instance is based on total number of days of record. Each portion of the curve represents the percent of a composite day that a particular flow occurs for the period of record. For example, in Figure 4-13 a discharge of 100 cfs or greater occurs for 10 percent of a composite day. The use of a long record of water discharge for the flow duration curve greatly improves the reliability of the average annual sediment yield obtained when only a short-time suspended load record is available. Methods of flow-duration curve preparation are discussed in detail by Searcy (1959).

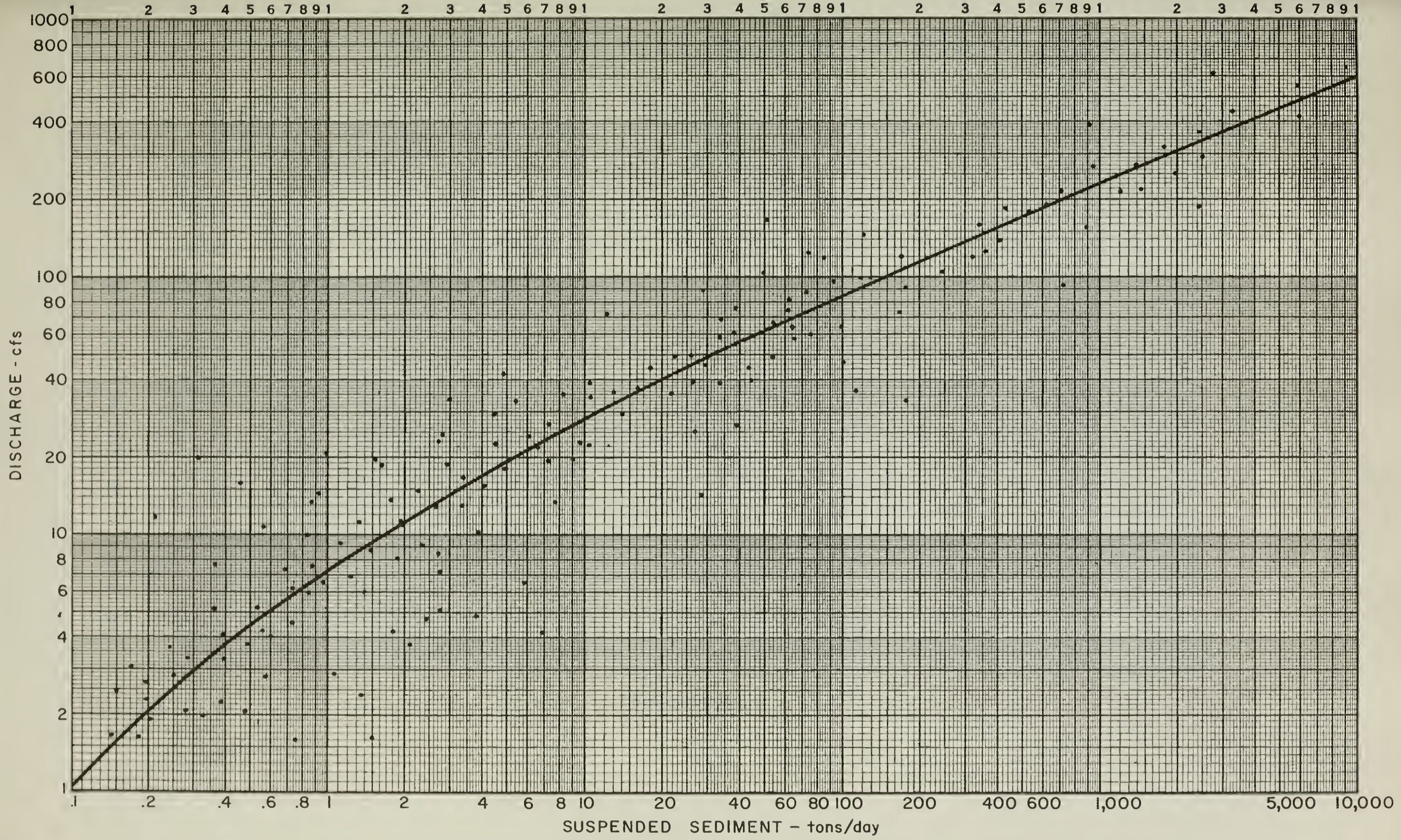


Fig. 4–12.– Sediment rating curve, Cottonwood Creek, any state

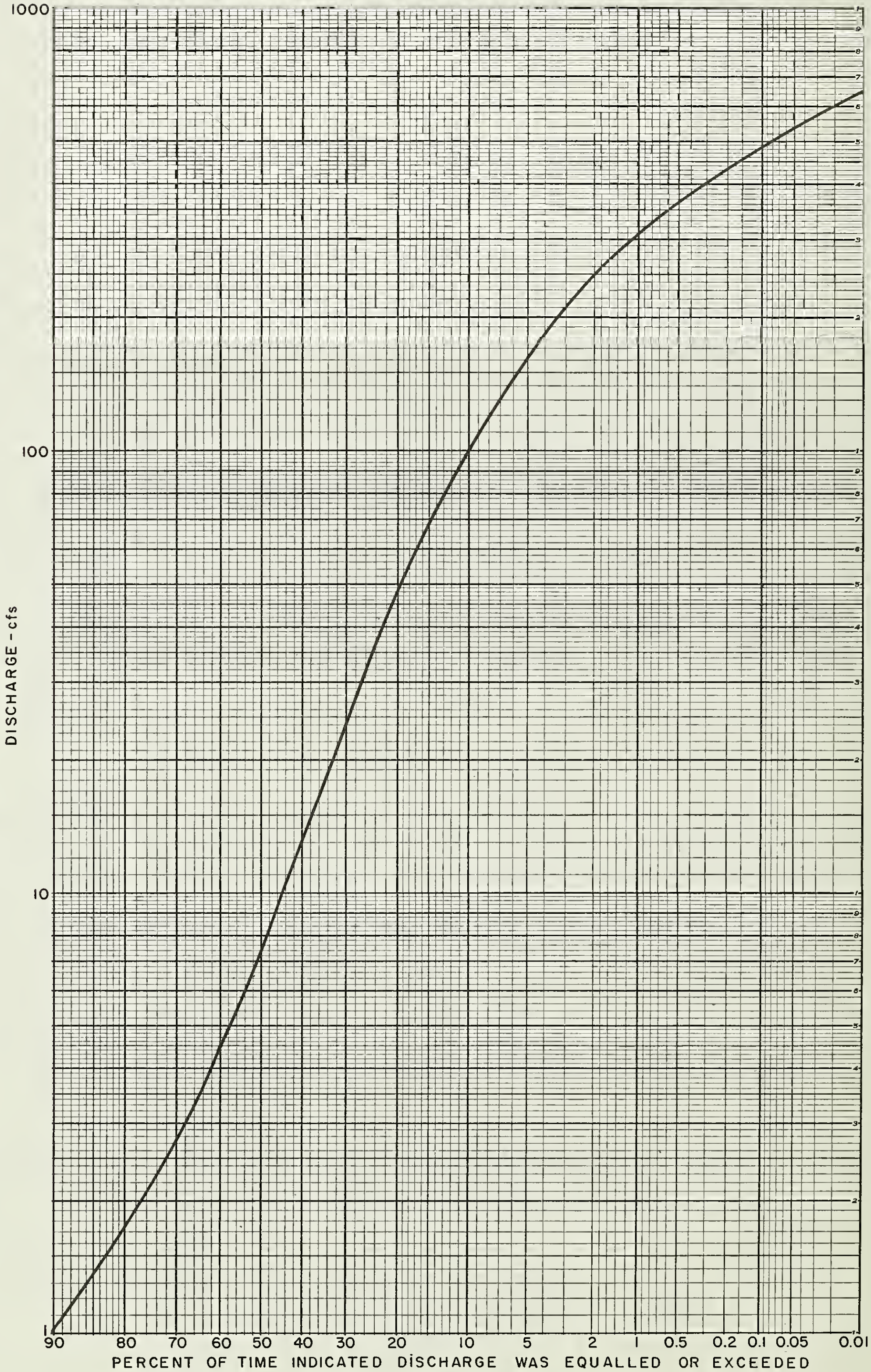


Fig. 4-13.- Flow Duration Curve Cottonwood Creek, any state

TABLE 4-5 Average annual suspended sediment load computation Cottonwood Creek, any state

| 1<br>Percent<br>Limits | 2<br>Percent<br>Interval | 3<br>Percent<br>Mid. Ord. | 4<br>Discharge<br>cfs<br>Qw | 5<br>Sediment<br>Load - Tons<br>Qs | 6<br>Col. 2(4)<br>Qw Disch.<br>per day | 7<br>Col. 2(5)<br>Qs Disch.<br>per day |
|---|---|---|---|---|---|---|
| 0.01-0.05 | .04 | 0.025 | 590 | 9000 | 0.24 | 3.6 |
| 0.05-0.1 | .05 | 0.075 | 510 | 6400 | 0.25 | 3.2 |
| 0.1 -0.5 | .4 | 0.30 | 400 | 3500 | 1.6 | 14.0 |
| 0.5 -1.5 | 1.0 | 1.0 | 310 | 1900 | 3.1 | 19.0 |
| 1.5 -5 | 3.5 | 3.25 | 200 | 700 | 7.0 | 24.5 |
| 5 -15 | 10 | 10 | 100 | 145 | 10.0 | 14.5 |
| 15 -25 | 10 | 20 | 47 | 28 | 4.7 | 2.8 |
| 25 -35 | 10 | 30 | 25 | 8 | 2.5 | 0.8 |
| 35 -45 | 10 | 40 | 13 | 3 | 1.3 | 0.3 |
| 45 -55 | 10 | 50 | 7 | 1 | 0.7 | 0.1 |
| 55 -65 | 10 | 60 | 4 | 0.5 | 0.4 | 0.05 |
| 65 -75 | 10 | 70 | 3 | - | 0.3 | - |
| 75 -85 | 10 | 80 | 2 | - | 0.2 | - |
| 85 -95 | 10 | 90 | 1 | - | 0.1 | - |
| | | | | Total | | 82.8 |

Annual sediment discharge = 82.8 x 365 = 30,220 tons

On the table of computations, column 1 refers to a portion of the flow duration curve; for example, line 1 is for the portion between 0.01 percent and 0.05 percent, reading from right to left on the curve. Column 2 is the percent of time covered by this portion of the curve, or 0.04 percent, and 0.025 is the midpoint of this range, column 3. At the 0.025 level, the discharge shown on the flow duration curve is 590 cfs, column 4. Then referring to the sediment rating curve, the sediment discharge at 590 cfs is 9,000 tons, column 5. The data in column 6 reflects the contribution each subdivision of the flow duration curve makes to the composite daily discharge (not directly pertinent to a sediment yield problem) and column 7 is the same determination for sediment discharge. The sum of column 7 is a daily composite tonnage and when multiplied by 365 provides a yearly average total.

# APPENDIX TO CHAPTER 4
# TRANSPORTATION OF SEDIMENT BY WATER

## Derivation of Friction Factors for Flow in Sand Bed Streams by the Alam-Kennedy Procedure (Alam-Kennedy, 1969)

The following procedure was used to determine depth-discharge relationships for the problem described on pages 4-32 to 4-36. The procedure was developed from empirical data and it is designed to incorporate the impact of variable bed roughness on the flow and thus sediment transport. The hydraulic considerations involved were briefly discussed on pages 4-10 and 4-11. The authors believe the procedure is applicable over the full spectrum of bed forms and demonstrate it by comparing observed with predicted depth-discharge relationships. They use depth as equivalent to hydraulic radius, an assumption that would need to be adjusted for channels with substantial differences between the two. The effect of bank roughness should be evaluated under similar circumstances.

In illustrating the Alam-Kennedy procedure, an example is given from which the curves on Figure 4-16 were derived. The latter were then used in determination of sediment transport on Tables 4-1 and 4-2, where the Colby method with the Alam-Kennedy technique is listed.

In keeping with the problem as presented on pages 4-32 to 4-36, the bank influence is not taken into account, so that the hydraulic radius R is assumed equal to the hydraulic radius with respect to the bed, $R_b$.

Given: Channel slope = 0.002 ft/ft

$d_{50}$ size of bed material is 0.3 mm = 0.000984 ft

Assume the velocity = 3.5 ft/sec

Calculate the Froude number where

$$F_D = \frac{U}{\sqrt{g\, d_{50}}} = \frac{3.5}{0.178} = 19.66 \qquad (9a)$$

Assume $R_b$ = 1.30 feet

$$\frac{R_b}{d_{50}} = \frac{1.30}{0.000984} = 1321 \qquad (9b)$$

Assume $\nu = 10^{-5}$ ft$^2$/sec

$$R_N = \frac{UR_b}{\nu} = \frac{3.5(1.3)}{10^{-5}} = 4.55 \times 10^5 \qquad (9c)$$

From Figure 4-14, using the foregoing values of $U/\sqrt{g\ d_{50}}$ and $R_b/d_{50}$, obtain $f_b''$ (Darcy-Weisbach bed form friction factor).

$$f_b'' = 0.025 \tag{9d}$$

From Figure 4-15 (Lovera and Kennedy, 1969) obtain $f_b'$ (flat bed friction factor) using the preceding values of $R_N$ and $R_b/d_{50}$

$$f_b' = 0.20 \tag{9e}$$

The total friction factor, $f_b = f_b' + f_b'' = 0.020 + 0.025 = 0.045$ (9f)

Calcultate the hydraulic radius.

$$R_b = f_b \frac{U^2}{8gS} = \frac{0.045(3.5)^2}{8g(0.002)} = 1.07 \tag{9g}$$

Since the calculated and assumed values differ by what is assumed to be an excessive amount, the preceding steps are repeated using the new value of $R_b$.

$$\frac{R_b}{d_{50}} = \frac{1.07}{0.000984} = 1087 \tag{9h}$$

$$R_N = \frac{UR_b}{\nu} = \frac{3.5(1.07)}{10^{-5}} = 3.75 \times 10^5 \tag{9i}$$

From Figure 4-14, $f_b'' = 0.023$.

From Figure 4-15, $f_b' = 0.023$.

$$\text{Then } f_b = f_b' + f_b'' = 0.023 + 0.023 = 0.046 \tag{9j}$$

$$R_b = f_b \frac{U^2}{8gS} = \frac{0.046(3.5)^2}{8g(0.002)} = 1.09 \tag{9k}$$

Since the difference between calculated and last assumed value of $R_b$ is less than two percent, additional computation is unjustified.

$R_b = 1.09$

$U = 3.5$

$q = 3.8$ cfs/ft

The above steps were repeated for velocities of 2.0, 5.0, and 6.2 feet per second in order to provide data for the $R_b$-velocity curve on Figure 4-16. The $R_b$-discharge curve on Figure 4-16 was then plotted. Both curves were then used for the derivations on Tables 4-1 and 4-2 of the Colby procedure.

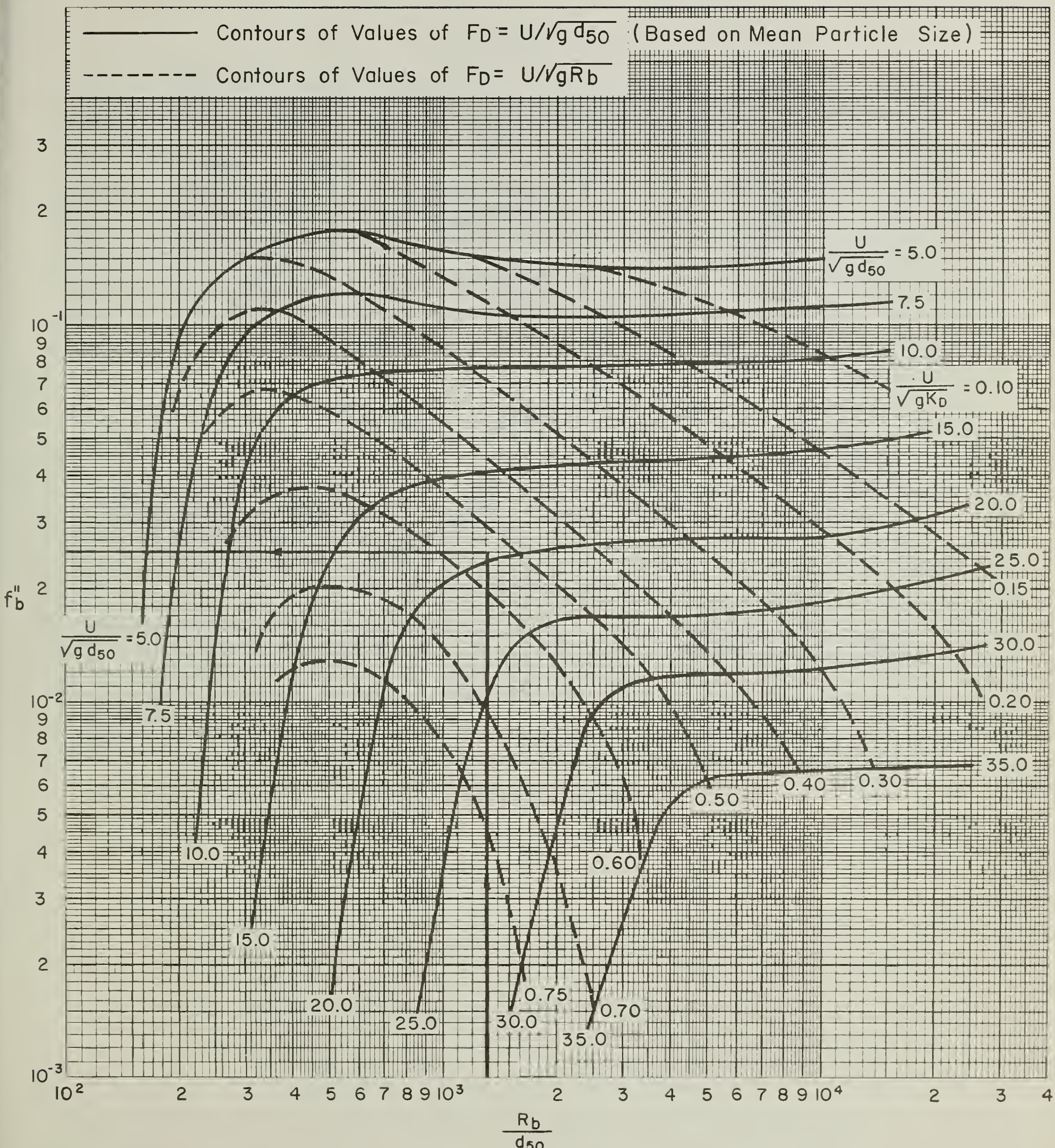


Fig. 4-14.- Form-drag friction factor in sandbed channels, $f''_b$ as a function of $R_b/d_{50}$ and $F_D = U/\sqrt{g d_{50}}$ (From Alam and Kennedy, 1969, p.1983)

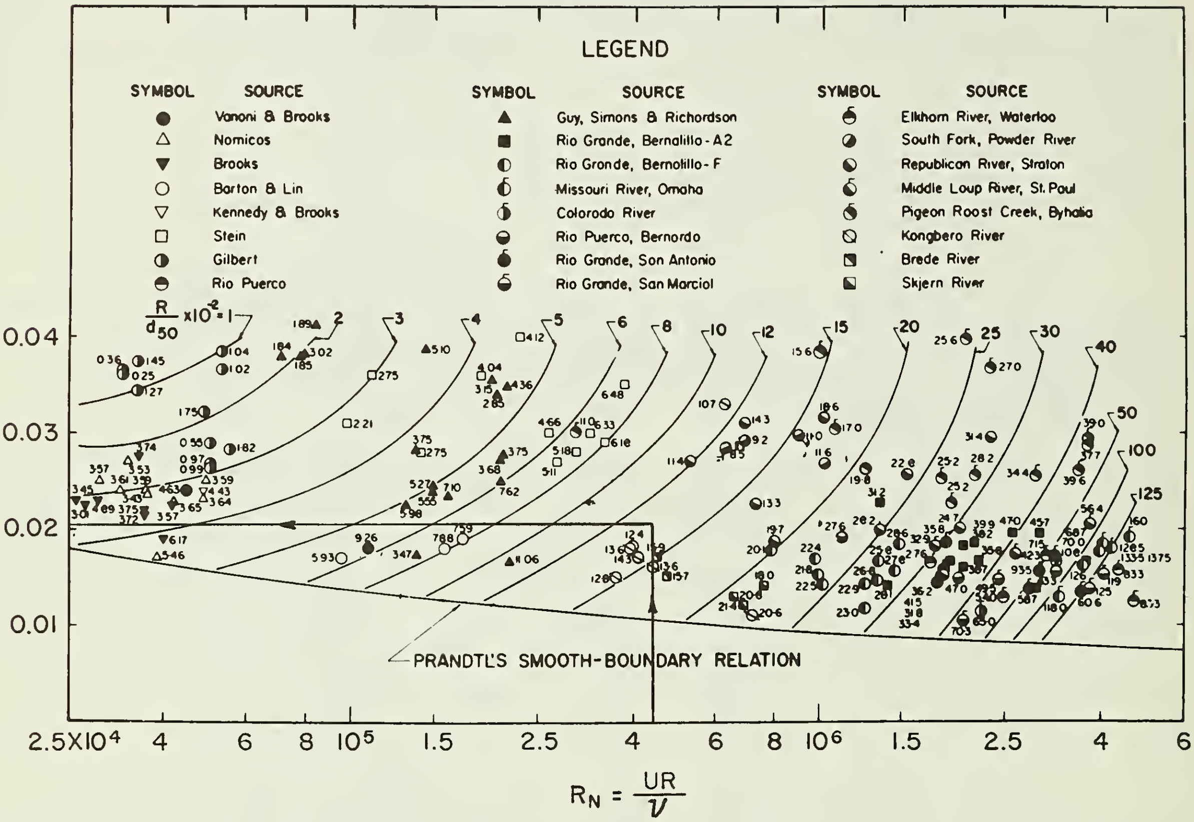


Fig. 4-15.- Friction-factor predictor for flat-bed flows in alluvial channels (the number by each point is $R/d_{50} \times 10^{-2}$ (From Lovera and Kennedy, 1969, p.1230)

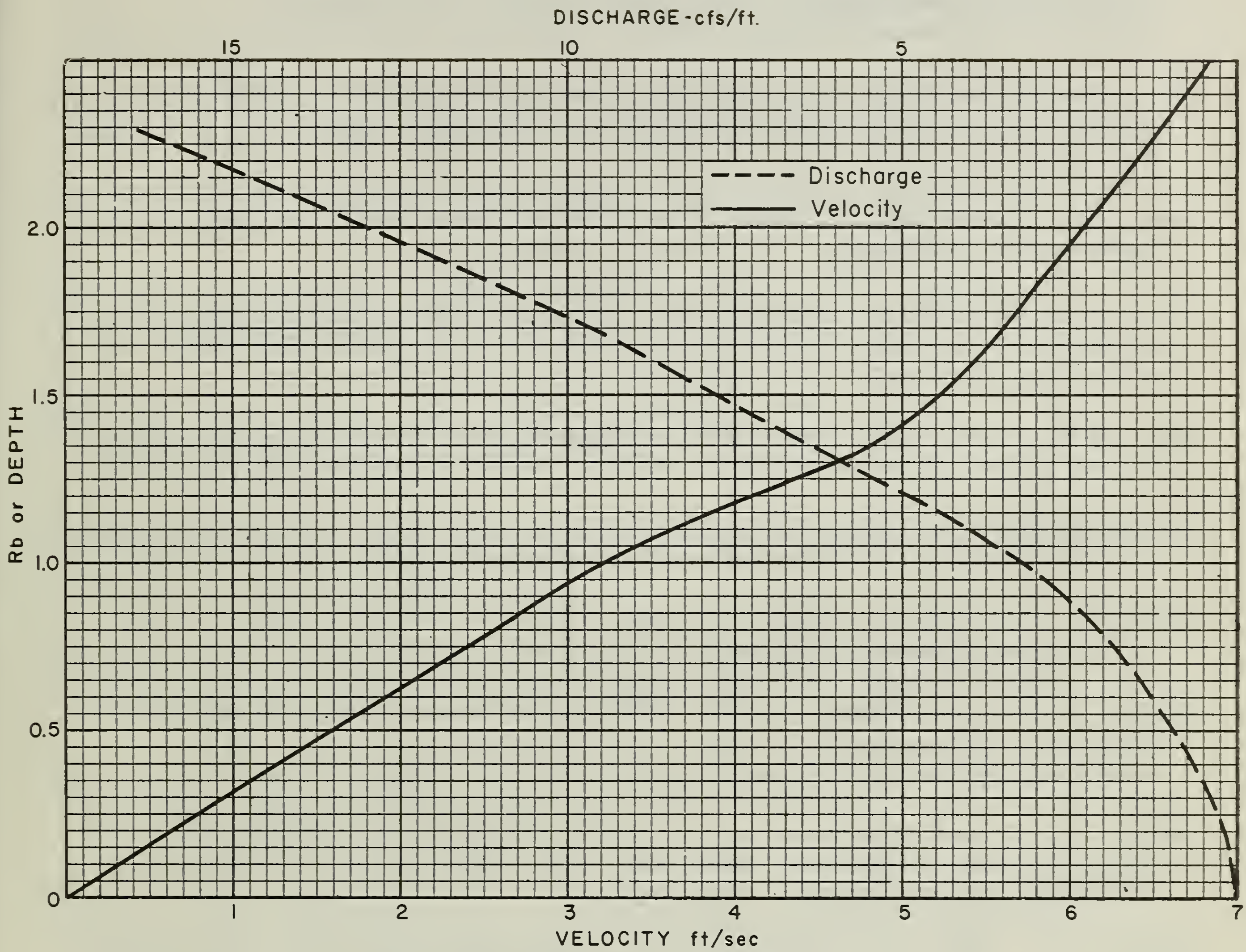


Fig. 4-16.- Depth-discharge relationships using Alam-Kennedy technique.

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NATIONAL ENGINEERING HANDBOOK

SECTION 3

SEDIMENTATION

# CHAPTER 5. DEPOSITION OF SEDIMENT

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NATIONAL ENGINEERING HANDBOOK

SECTION 3

SEDIMENTATION

# CHAPTER 5. DEPOSITION OF SEDIMENT

## General

This chapter concerns the various types of sediment deposits, and the physical damage that these deposits cause[1/]. Geologists of the Soil Conservation Service (SCS) identify many types of sediment deposits and their rates of deposition as compared to natural or geologic rates. These investigations are concerned chiefly with those sediment deposits occurring on flood plains and in channels and reservoirs. The deposits are discussed in the general sequence in which they may occur from the uplands to the sea.

Common types of physical damage caused by sediment deposition are:

1. Burial of fertile soils by less fertile sediment.

2. Damage to growing crops and burial of crops.

3. Impairment of drainage with accompanying rise of the water table and an increase in swampy areas of alluvial land.

4. Filling of channels causing more frequent flooding and increased flood heights. Channel filling may result in changes of the channel course.

5. Filling of reservoirs and debris basins.

6. Damage to railroads, bridges, roads, power lines and other facilities. Ditches and road grades may be filled to a degree where regrading is needed.

7. Urban areas particularly with homes and commercial and industrial buildings damaged by sedimentation and increased flood heights.

8. Damage to recreational facilities.

As appropriate the damages are ordinarily calculated in terms of restoration to original conditions or by loss of productivity or services. The geologist and economist work closely together in determining damage. The geologist obtains information on physical damage and the economist arrives at cost evaluations based on this information.

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1/ See descriptions by Twenhofel (1950), Trask (1950), Krumbein and Sloss (1963), and Gilluly et al (1968).

## Fan Deposition

### Nature of Occurrence

The typical alluvial fan is an accumulation of sediment brought down by a stream descending through a steep ravine or canyon. Consequently, when the stream emerges from the confined area with a loss of velocity most of the sediment is dropped and spreads out in the shape of a fan. The fan is roughly semi-conical with the apex at the upper end. The sediment of an alluvail fan may range in size from fines to boulders. The streams which create and supply debris to fans are agents of vigorous erosion and they commonly transport enormous volumes of sediment. Boulders, cobbles and gravel are deposited at the upper end of fans and the finer sands, silts and clays are carried to lower elevations. (See Figure 5-1).

Figure 5-1 An Alluvial Fan
(Okanogan County, Washington)

Much of the stream water percolates through the porous coarse material of the fan. The spreading of flows plus the water lost through percolation causes deposition of the entire sediment load. The steepness and size of the alluvial fan varies with the geology, climate and

watershed size. The smaller the watershed, the steeper the fan other characteristics being similar. There is a considerable range in fan deposits from wide fans 10-100 miles across with slopes less than 1 degree, through fans with moderate width and slope (4-6 degrees), to relatively steep cones (up to 15 degrees) built of coarser debris transported by short torrential streams (Holmes 1965).

Streams on the fan characteristically change course frequently and develop a series of distributaries on the deposit. Fans may be isolated or may coalesce to form a long and broad alluvial slope. The development of many fans is characterized by erratic and sudden depositional events, especially in arid and semi-arid climates. Long periods of quiescence may be terminated by heavy rains producing torrential flows. The volumes of sediment deposited on fan areas below mountain slopes and canyons following heavy rains can be enormous. The deposits along mountain fronts in the United States are important because many of them are agricultural or urban areas and present problems difficult to control.

It has been reported by Dodge (1950) that a storm over the San Gabriel Mountains in 1934 in Los Angeles County, California caused deposition estimated at 88,000 cubic yards per square mile of drainage area. Since much of the fan area was occupied by urban and suburban developments, the damage was in the millions of dollars. In this instance the debris and sediment flows followed brush fires in the watershed during the preceding summer.

Damage caused by sediment-laden flows ranges from extreme maximums such as those of Los Angeles County to relatively small amounts following smaller, but more frequent, storms elsewhere. Many fans are forming at the foot of valley slopes in the Central Lowlands and even in the rougher parts of the Coastal Plains.

## Identification

Fan deposition occurs in many places, including valley slopes, and is not limited to a mountain environment. All fan deposits closely resemble the composition of the parent rocks from which they were derived, since relatively little chemical weathering has affected them. The coarse-textured sediment may vary from angular to round depending on the distance moved and the resistance of the rock to abrasion. The coarser sediment of the fan occurs near the top or apex of the fan where the slope is usually steeper. Near the base of the fan where the slope may decrease to one degree or less the grain size also decreases. Bedding is not distinct or regular as a rule in these deposits.

## Procedures for determining physical damages

The study of the damages being caused by fan deposition should begin with the preparation of a map showing the area affected. A general map should show the chief features of concern - drainage, topography, sediment sources, and the fan areas drawn to scale.

Measurement of the fan and its associated damages may be based on surveys to obtain the volume and also to determine textures and depths of deposit. The survey may be coordinated with a system of ranges to obtain cross sections of the valley. In the fan area the ranges should be spaced closely enough to show greater detail. Borings may be made along the cross sections or ranges to identify possible buried old soil horizons, although borings may not be conclusive at many points in a fan. The great thickness and coarseness of many fans may make measurements by boring impractical. Volume may be estimated by projecting the adjacent valley wall and the unaffected base to the valley wall. The investigation should be supported by the best historical records obtainable in order to get data on annual damages and volumes of deposition.

## Colluvial Deposition

### Nature of occurrence

The sedimentary products of upland erosion moved by gravity and by unconcentrated surface runoff, which accumulate on or near the foot of upland slopes, are known as colluvial deposits. This definition implies that the sediments comprising colluvial deposits have been transported relatively short distances from the sites of their detachment from soils or underlying formations. They represent some of the products of erosion which have not reached stream channels, reservoirs, or other points where measurements of sediment quantity and movement commonly are made. Since colluvial deposits are formed near the sites of erosion, they tend to accumulate where upland slopes decrease. This may occur at the foot of a slope leading into a valley, or at any place where the transporting power of the runoff, as overland flow, is lessened. Upland colluvial deposition, thus, is closely related to sheet erosion. They characteristically are narrow bands of sediment deposits having linear or sinuous shape. A reasonably complete survey of an area would provide information on the approximate volume of these deposits. This volume could then be subtracted from the calculated total erosion and the sediment yield to an area farther downstream be estimated. The history of land use and cultivation in the area should provide a basis for calculating annual contribution to the colluvial deposits.

The damages caused by colluvial deposits range widely from none to substantial amounts.

The basis of all damage estimates should be:

1. A map to show the extent of the area,

2. borings supported by local history for volume and rapidity of deposition,

3. the nature of the sediment, and

4. its effects.

## Flood-Plain Deposition

### Nature of occurrence

The flood plain is a strip of relatively smooth land bordering a stream and overflowed at times of high water (Leopold, Wolman, and Miller, 1964). The flood plain may vary in width from a few feet to several miles. It is a part of the stream transport system and, as such, carries water during times of flood.

In a valley where modern sedimentation is widespread the natural levees, which in many places are the dominant features, may be several feet thick. Away from the channel and natural levees the deposits of vertical accretion generally decrease in thickness toward the edges of the flood plain.

Where sedimentation from tributaries and valley slopes has been rapid, alluvial fans and colluvial deposits overlie the edges of the flood-plain deposit. If deposition in the main channel has been excessive, the channel may have become filled until its bottom elevation is raised above the surrounding flood plain. Then subsequent flood flows may follow an entirely different course. In some valleys modern sedimentation has caused substantial damage to the flood plain, but has not formed a continuous valley-wide deposit.

The following descriptions of flood-plain deposits are from Happ, et al (1940).

Vertical-accretion deposits.-- In times of flood, the stream channels lack the capacity to carry all of the water delivered to them as surface runoff. The excess water overflows the banks and spreads over the adjacent flood plain. Because of greater frictional resistance, this spreading results in a marked reduction of velocity and an even greater reduction in transporting capacity. Part of the sediment which was carried in suspension while the water was confined to the channel is therefore deposited on the flood plain. As the velocity decreases the coarser material is dropped first and builds up the characteristically sandy natural levees that border the channels. Finer sediment is carried farther from the channel and deposited as a thinner layer over the entire flood-plain surface. This is the process of vertical accretion and the deposits are composed almost entirely of sediment which was carried to the place of deposition as suspended load. In this respect they differ from the channel deposits, which are largely composed of bed-load sediment. See Figure 5-2.

Flood-plain splays.-- The regularity of flood-plain deposition is interrupted in those places where excess water leaves the channel through restricted low sections or breaks in the natural levees. In such places the velocity of the escaping water may be enough to carry along an appreciable amount of relatively coarse sediment and carry it farther from the channel than would otherwise be the case. The sandy

Figure 5-2 Vertical accretion, subsoil over topsoil in creek bottom, Fairfield County, Ohio

sediment is commonly spread outward onto a fan-shaped area of the flood plain, across which it is moved forward at least partly as bed load. These deposits are flood-plain splays.

Other deposits.-- Colluvial deposits occur on the flood plain at the base of bordering slopes. They are composed chiefly of the debris from sheet erosion deposited by unconcentrated surface runoff, together with talus and other mass-movement accumulations.

Older channel deposits underlie much of the flood plain. The description of channel-fill deposits, lateral-accretion deposits and valley-plug deposits may be found under channel deposition beginning on page 5-8.

Identification

Identification of deposits formed by modern accelerated deposition is based chiefly upon proper distinction between modern sediment and the buried original flood-plain soil. Since the characteristics of both the sediment and the buried soils are different in different valleys, these relationships must be investigated when beginning a valley survey. A list of important criteria, upon which distinctions can be based, follows.

Texture.-- Modern sediment is coarser, in most cases, with a greater range in texture, whereas buried soil is usually finer with more uniformity.

Color.-- Modern sediment is generally a lighter color which may vary with texture, whereas buried soil is generally darker and more uniform. A gray or greenish-gray staining of modern sediments may be present as a result of a former high ground-water table.

Compaction.-- Modern sediment is less compact and less cohesive than buried soil.

Distinctive minerals.-- Modern sediment may contain grains of micas, gypsum, feldspars, calcite or other easily weathered minerals, whereas very few grains of easily weathered minerals are contained in buried soil. Buried soil usually contains more clay minerals than does modern sediment.

Evidence of cultural activity.-- Modern sediment may cover or contain buried boards, tools, bricks, fences and other man-made objects, and buried tree stumps.

Stratification.-- In many cases modern sediment has distinct stratification with cross-bedding and lenticular beds.

Procedures for determining the extent of deposition

A survey of a watershed area should include a study of all the important valleys. Information having a bearing upon erosion rates,

sediment yields, and flooding should be summarized. This should include valley width and depth, nature of the slopes, chief rock outcrops, nature and extent of terraces and relationships to channels. These features all have a direct influence upon the quality and magnitude of the sediment deposits (see Chapter 7; and Roehl and Holeman, 1970).

## Channel Deposition

### Nature of occurrence

Deposition in channels occurs in connection with stream action in many situations and environments including alluvial fans, larger river valleys, distributaries and passes of deltas, and alluvial plains of great extent. Deposits resulting from channel fill, and lateral accretion may be found throughout the flood plain. Only deposits currently forming will be restricted to the present channels. See Figure 5-3.

### Identification

In general, it should be recognized that an accumulation of sediment deposits in a channel is the result of the inability of the stream to carry all or a part of its load.[2/] Generally the coarsest sediment deposits occur in and along the channel. If the history of accelerated deposition has been rapid, the channel may be partly or completely filled so that future flood flows follow an entirely different course. These deposits can be identified by their coarser texture, sinuous shape, and damages such as filled channelways and bridge openings and new areas of swamping.

Channel-fill deposits.-- These occur in the stream channels where the transporting capacity has been insufficient to remove the sediment as rapidly as it has been delivered. The process has not been a simple sorting out and deposition of the coarsest material, but a net accumulation from alternate scouring during rising flood stages and deposition during the falling stages. As the average amount of scour has been less than the average amount of deposition, the net result has been aggradation of the channel bed. Channel deposits are relatively coarse textured except in areas of fine-grained sources such as loess and shales. See Fig. 5-4, on page 5-11.

Valley-plug deposits.-- These are always associated with filling of the stream channel. When the channel has been completely filled at one place the area of deposition moves upstream by backfilling. At the same time the water flowing in the channel is forced overbank, where it drains down valley, as through back-swamp areas (defined on p. 5-10), until it again collects into definite channels and eventually returns to the main channel.

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[2/] This process is described by Happ (1940), Brown (1950), Einstein (1950), Leopold, et al (1964), Happ (1971) and others.

Figure 5-3 Channel fill, lateral and vertical accretion in Winona County, Minn.

Plugs in general are caused by a decrease in the capacity of the stream channel downstream. The decreased channel capacity may result from such things as jams of driftwood, fallen trees, delivery of sediment from a tributary in such quantities as to choke completely the main stream channel, or inadequate artificial channel modification downstream. The cause of the original channel obstruction may not be evident.

Lateral-accretion deposits.-- These are formed along the sides of channels, where bed-load material is moved by traction toward the inner (convex) sides of channel bends. Normally such deposits of lateral accretion are later covered by finer material of vertical accretion, as the channel shifts farther away by lateral bank cutting so that the slip-off slope on the inside of the bend is overflowed less frequently and with less velocity.

Procedure for determining physical damages

The quantity and damage of channel deposits should be measured by borings to determine thickness, by mapping to determine extent, and by getting the most recent history available to determine frequency of depositional events. Information on channel and bridge clearing, as well as road clearing, may be available from county engineers' offices and if so can be used as one measure of the damage caused by channel action. The information gathered may include;

1. The volumes of channel and bridge clearing.

2. The measurement of areas where channel action has raised water tables. These depths and areas should be measured and mapped.

3. The increase in the flood hazard and damage. They can be investigated and evaluated along the ranges of the watershed survey.

Associations of the flood-plain and channel deposits

In the normal flood-plain association of sediments, vertical-accretion deposits cover coarser deposits of lateral accretion and channel fill. The vertical-accretion deposits cover the flood plain with a fairly uniform thickness of fine sediments sloping away from the channel to the valley sides. The deposits of vertical accretion are the chief sources of the fertile bottom-land in most valleys.

Modern channel-fill deposits occur in the present channel and in abandoned channels. In the latter case they may be covered by vertical-accretion deposits. Sand splays occur immediately alongside present or former channels and interfinger into the vertical-accretion deposits. Colluvial deposits interfinger into the vertical-accretion deposits from the valley sides. The characteristically low area between the natural levees and the colluvial deposits is called the back-swamp part of the flood plain. The characteristics of the different types of deposits in the normal flood plain association are summarized in Table 5-1.

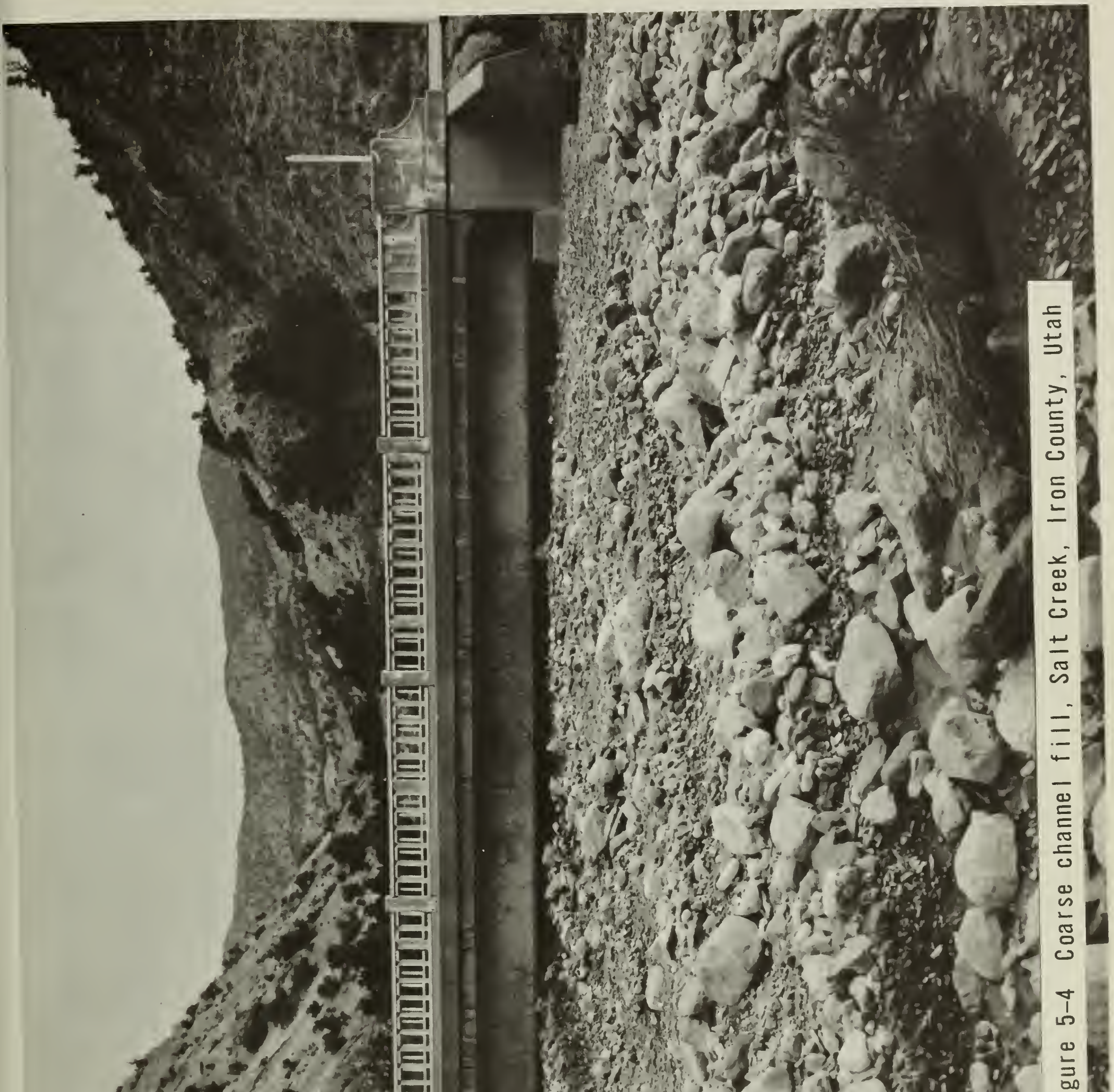

Figure 5-4 Coarse channel fill, Salt Creek, Iron County, Utah

Table 5-1. Characteristics of genetic types of valley deposits

| | Types of deposits | | | | |
|---|---|---|---|---|---|
| | Colluvial | Fluvial | | | |
| | | Vertical accretion | Splays | Lateral accretion | Channel fill |
| Principal origin | Concentration by slope wash and mass movements | Deposition of suspended load | Deposition of bed load | Deposition of bed load always prominent, but suspended load may be dominant | Deposition of bed load and suspended load |
| Usual place of deposit | At junction of flood plain and valley sides | On entire flood-plain surface | On flood-plain surface adjacent to the stream channel | Along side of channel especially on the inside of bends | Within the channel |
| Dominant texture | Varies from silty clay to boulders | Dominantly silt; often sandy, especially near channel; often much clay | Usually sand; may be gravel or boulders | Sand or gravel; may include silt or boulders | Usually sand, silt, and gravel; may include clay or boulders |
| Relative distribution in the valley fill | Interfinger with the fluvial deposits along outer margins of flood plain | Overlie deposits of lateral accretion and channel deposits; overlain by or interbedded with splay and colluvial deposits; usually cover most of flood-plain surface | Form scattered lenticular deposits overlying or interbedded with vertical accretion deposits adjacent to present or former channels | Usually overlain by vertical accretion deposits, often underlain by channel-fill deposits; may extend across entire flood-plain width | Usually from elongate deposits of relatively small cross section, winding through flood plain; may underlie vertical accretion deposits |

## Sediment Deposits in Reservoirs

Only a generalized description of sediment deposits in artificial basins is presented in this handbook. Additional details on reservoir sedimentation are given by many investigators[3]. Measurement and evaluations pertaining to reservoir sedimentation are discussed in other parts of this handbook such as Chapter 6, Sediment Sources, Yields and Delivery Ratios; and Chapter 7, Field Investigations and Surveys.

### Character and distribution

An impounding reservoir designed so that the water level fluctuates within a small range, has a typical texture and distribution of sediment deposits. The bulk of the deposit normally is clay and silt distributed more or less evenly over the reservoir bottom. Nearly all of the coarser particles, including sand, gravel and boulders, are deposited in or near the head of the impounded pool where the velocity of inflowing currents is reduced. The silt and clay particles remain longer in suspension, and are spread widely over the reservoir bottom. Some sands, gravels, and poorly sorted deposits may occur in relatively narrow shore zones, especially if active wave erosion has occurred. The composition and texture of the beach deposits depend upon the nature of the shore (Jones and Rogers, 1952 and Jones, 1954).

If the water levels in a reservoir fluctuate widely, the character and distribution of the sediment deposit are both changed considerably. When the withdrawal of water is large and this increased use coincides with a period of drought, the water level in the pool may shrink to very low levels or the reservoir may be completely drained. Under the resulting exposure to atmospheric conditions the clay and silt may become partly desiccated, shrink in volume, and add to the existing capacity of the reservoir. Repeated surveys by the SCS have shown this; as an example, the capacity of Medina Lake in Texas has been partly restored in this manner at least three times in its history.

In contrast to a broad equitable distribution of the sediment in many impounding reservoirs, some changes in distribution of previously deposited sediment may result from sudden large inflows which occur during or following periods of low water levels. The upstream parts of the channels may be scoured and coarse sediment from the upstream segments transported downstream to be deposited in areas previously occupied only by clays and silts. This process has occurred repeatedly in reservoirs such as Lakes Abilene, Nasworthy, and Waco, in Texas, and in larger impoundments such as Lake Texoma, Alamagordo, and Elephant Butte Reservoirs. Coarse texture of the incoming sediments tends to concentrate the deposition at and near

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[3] As Stevens (1936), Eakin & Brown (1939), Noll, Roehl and Bennett (1950), Holeman and Geiger (1959), and Gottschalk (1965).

the head of a reservoir. A careful study of the deposits during a reservoir survey can yield much data regarding the sources and the formation of the reservoir deposit. Figure 5-5 shows typical distribution of sediment in a number of reservoirs. Figure 5-6 shows excessive sediment accumulation.

Volume Weight

The volume weight of a substance is its weight per unit volume. It is also at times called dry density and specific weight. This important property of sediments has been discussed briefly in Chapter 2 (p. 2-16) and some data are presented on the volume weights of reservoir sediments (p. 2-17). In general, greater compactness in sediments results from heavier overlying loads, greater age, and subtraction of water. The volume-weights of sediments also are affected by the operation of the reservoir; the pools in which they occur; and the weather which affects them; as well as by the sorting and composition of the sediment. Generally, the soils and underlying rocks occupy more space after being eroded and deposited in a reservoir than when in place in a watershed[4/]. In planning floodwater-retarding structures and similar works it has been found that the sediment carried into the pools will occupy from 1.1 to about 1.4 times the space of the same soil in place in the watershed.

Procedures for determining physical damages

The evaluation of sediment damage to reservoirs is usually conducted by one of four different methods. These are referred to as (1) straight line, (2) sinking fund, (3) sinking fund plus service loss, and (4) cost of sediment removal. These are the methods used by SCS economists in the determination of monetary damages to reservoirs due to sedimentation and the monetary benefits derived from recommended soil conservation programs (SCS, 1964). The geologist should work closely with the economist to determine the type of economic analysis which should be made and the type of field data needed for the specific type of analysis proposed.

Briefly, in the straight line method the average annual damage is estimated as the product of the average annual rate of storage loss in acre-feet due to sedimentation, and the original cost per acre-foot of the storage. The geologist must determine the average volume of sediment expected to be deposited annually with and without the recommended soil conservation program installed. Where sediment damage to existing reservoirs is to be evaluated, for example in water supply reservoirs, the present annual rate of sediment deposition can be determined by a reservoir survey as described in Chapter 7. The future rate of sediment deposition, after the completion of the recommended soil conservation program, can be determined by the same methods as used for sediment design of proposed reservoirs.

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[4/] This has been investigated by Brown and Thorp (1949), Gottschalk and Brune (1950), Jones (1952), Glymph (1954), Koelzer and Lara (1958), Lara (1970), and others.

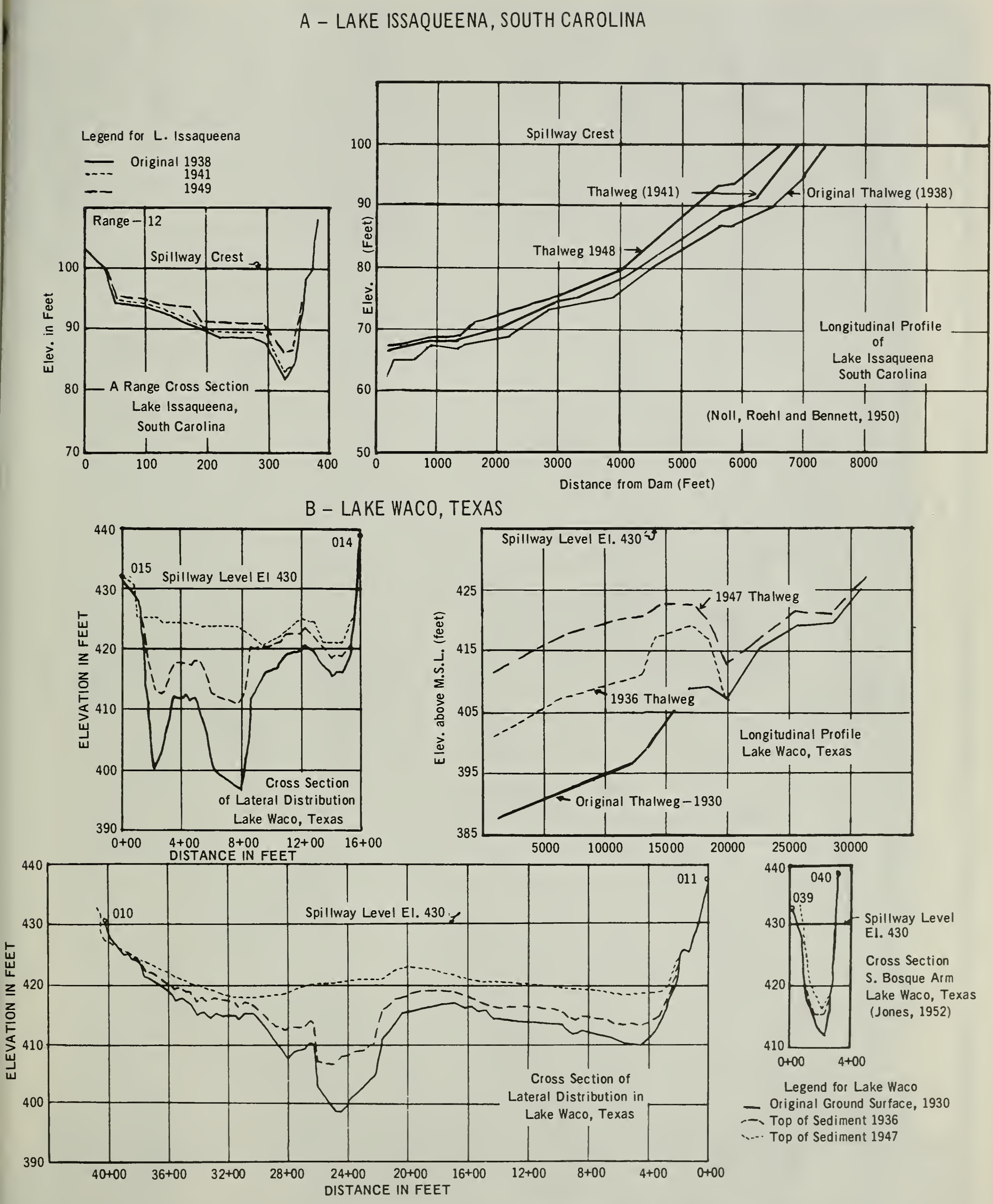


Figure 5-5 Examples of Sediment Distribution In Reservoirs

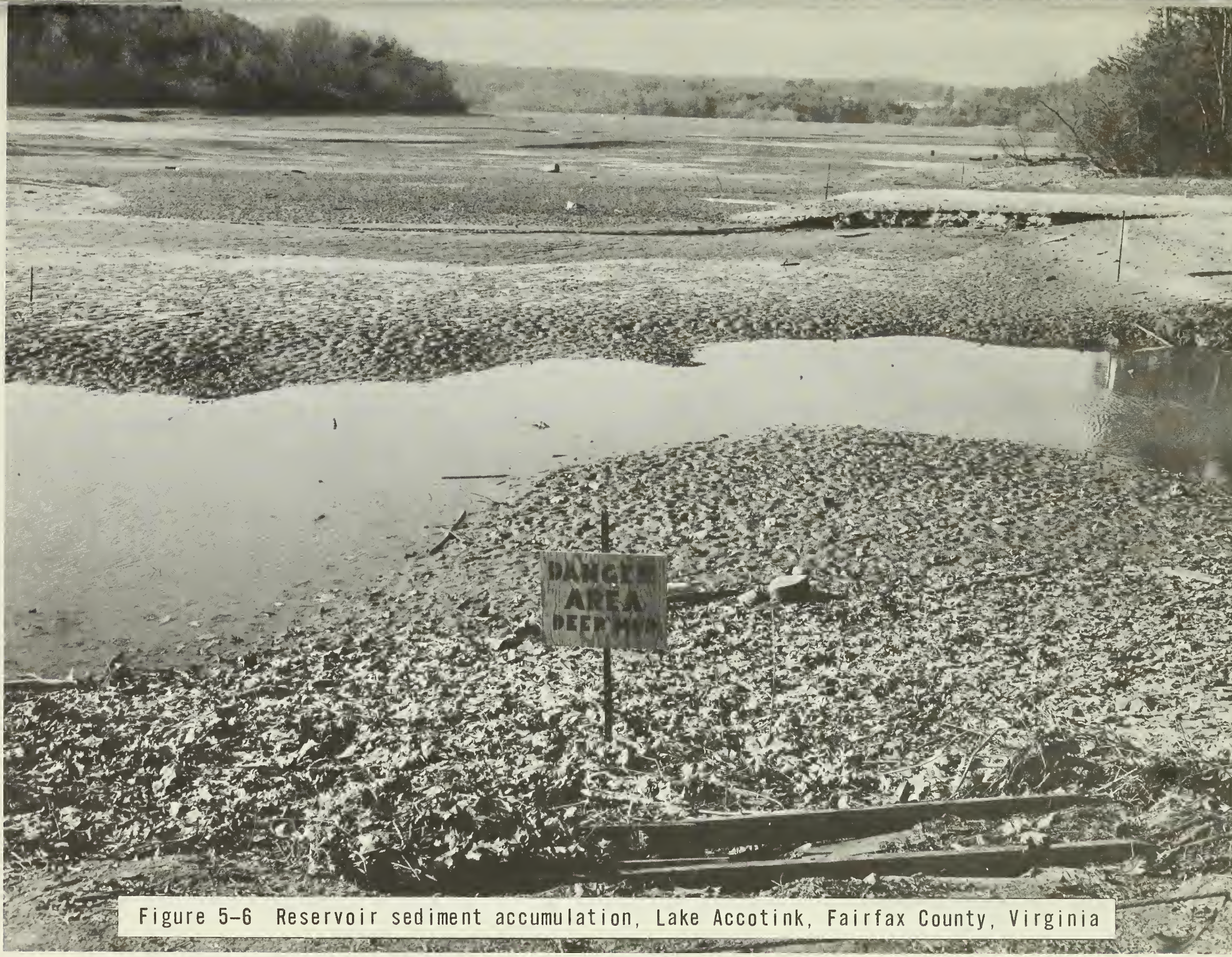


Figure 5-6  Reservoir sediment accumulation, Lake Accotink, Fairfax County, Virginia

The sinking fund and the sinking fund plus service loss methods of evaluation are used when available information clearly indicates that a reservoir will be replaced prior to any significant loss in services. In these methods, the useful life of the structure, with and without the recommended soil conservation program, must be determined in addition to the average annual rate of sediment accumulation.

Evaluation of reservoir sedimentation damages on the basis of cost of sediment removal requires estimating, in addition to the sediment yield, the average annual amount of sediment to be removed without the program and with the program. This method is used when information indicates that reservoir storage will be maintained by the removal of sediment.

The method selected to evaluate damage to reservoirs will depend upon the amount of information that is available or can be obtained within the limitations of time and budget and the importance of the benefits accruing from reduced rates of reservoir sedimentation. The straight-line method is simple to use and is the preferred method (SCS 1964, pp. 5-20).

## Sediment Deposits in Harbors and Estuaries

### Nature of occurrence

The effect of tides and river discharge causes mingling of fluvial and beach deposits in such a manner that the deposits are heterogeneous both in character and distribution. One of the chief problems affecting the use and maintenance of harbors is sediment accumulation in their basins and channels. This requires costly dredging and other measures to maintain ship channels and docking facilities. Available records indicate that accelerated upland erosion and the resulting increased sediment loads have greatly increased deposition in harbors since agriculture and industry have developed in the United States. Many records of this increase in deposition are available. Figure 5-7 is an example.

### Identification

The identification of deposits in harbors and estuaries depends upon two chief lines of investigation. One concerns the sediment transported into the area by inflowing streams. The other concerns sediment produced by erosion of the shores and in the re-entrants of bays under investigation. Minerals either along the shores or transported into the area may be sufficiently distinctive so that they can be identified in the shore or outer bay deposits. If these minerals can be identified and traced, some data on the relative importance of these sources of sediments which occur in the bay and shore deposits can be assembled. Similarly this type of mineralogical relationship can be applied to sediment which may be contributed from industrial plants and other sources in the area.

Procedures for Determining Physical Damages

Some investigation of sedimentation in harbors has been made by the Soil Conservation Service. Brown (1939) reported on deposits of the York River estuary in Virginia. Holeman (1962) reported that by 1960 141,000,000 cubic yards of sediment had been removed from Baltimore Harbor since 1836 by Federal agencies at a cost of $26 million. A good source of information on sediment removed by dredging to maintain harbors is the reports of the Corps of Engineers, including annual reports by the Chief of Engineers and those of the District offices. A comparison of aerial photographs taken years apart of harbors and estuaries not subject to dredging may give an indication of the rate of sediment accumulation, as shown in Figure 5-7.


Figure 5-7 Sediment-filled estuary at Joppa Town, Maryland

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SECTION 3

SEDIMENTATION

# CHAPTER 6. SEDIMENT SOURCES, YIELDS AND DELIVERY RATIOS

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SECTION 3

SEDIMENTATION

# CHAPTER 6. SEDIMENT SOURCES, YIELDS AND DELIVERY RATIOS

## Introduction

### General

Sediment yields are dependent on erosion processes at the sediment source and the efficiency of the medium, usually streamflow, in transporting the sediment to the point of measurement. The amount of sediment yield usually varies at different locations in a stream system. Many factors influence the yield and these are interrelated in cause and effect.

Knowledge of each of these items is important for many reasons. Among the reasons are the needs to:

1. Evaluate downstream sediment damages,
2. Determine the location and extent of sediment sources so effective controls can be planned and installed,
3. Recognize the relative importance of the various sources to estimate present and future sediment yields, and
4. Determine the sediment storage requirements for the design of proposed structural works of improvement.

This chapter presents procedures for determining sediment sources, sediment yields and sediment delivery ratios.

### Interrelationship of processes

Sediment yield is dependent on gross erosion in the watershed and on the transport of eroded material out of the watershed. Only a part of the materials eroded from upland areas in a watershed is carried out of the watershed. Varying proportions of the eroded materials are deposited as colluvium at the base of slopes and in swales or, as alluvium in natural or artificial lakes, on flood plains and in channels within the watershed. Therefore, the magnitude of yield usually varies for different parts of a watershed.

Field determinations of sediment yield may involve long-term sampling and measuring procedures. An alternate short-term procedure is to transpose (and adjust as appropriate, p. 6-7) established sediment yields from measured watersheds in the same physiographic section in which conditions are similar to the watershed in question.

## Sediment Sources

### General

Sources of sediment must be delineated in order to formulate an adequate program for reducing downstream sediment yield. Individual sediment sources include agricultural land; range and forest land; road banks and ditches; stream channels and banks; flood plains; spoil banks; gullies; and others. In the development of a program to reduce sediment yields, the relative importance and method of treatment of the different sources must be determined in order to ascertain the physical and economic feasibility of the program. Sediment derived from sheet erosion can normally be controlled by land treatment measures, whereas that derived from channel-type erosion usually requires structural works.

A sediment source study is made: (1) to locate the origin of the sediment; (2) to determine the rates of erosion from each type of source; (3) to ascertain what portion of the sediment is derived from each source; (4) to determine, for program formulation and/or structure design, what types of treatment can and should be recommended for reducing sediment yield and/or controlling waterborne sediment; and (5) to determine what the relative effects of reducing the various sources will have in reducing sediment yield and damages.

The relative importance of the sources of sediment may differ at different locations in a watershed. Therefore, the emphasis on various treatment measures may also vary depending on the location in the watershed where a reduction in sediment yield is desired.

### Determining the relative importance of various sources

The following general items should be given consideration in the early stages of any study made for determining the location, extent, and relative importance of sources of sediment.

Use of maps and aerial photographs.--A careful review of aerial photographs will often reveal where severe erosion is occurring and which channels appear to be carrying the heaviest load of sediment. If soil surveys are available, the information on soils, slopes, land use, and erosion conditions recorded on the maps is a great help in generally locating sediment sources. All such information should be used to the fullest extent. Such use will save considerable time in locating the most obvious sources of sediment.

Distinctive minerals.--The presence of distinctive minerals in the modern sediment deposits is helpful in identifying and evaluating sediment sources. Since one watershed may contain several rock formations, the products of accelerated erosion of these formations may furnish good indications of the location of erosion sources. Such distinctive minerals may be quartz, micas, iron oxide fragments, feldspar, chert, limestone or calcite fragments, or others. Some of them can be easily identified and traced to their original source. Other

watersheds are underlain by more uniform rocks and hence may not provide such specific clues to the location of significant erosion. This means of identification must be used with discretion because it may or may not be significant.

Colluviation.--Another guide to an evaluation of sediment sources is the extent and location of colluvial deposition. If a coarse-grained material such as sand or gravel is being actively eroded, it may furnish large volumes of sediment, little of which reaches a locality very far removed from the site of erosion. Substantial deposits may be formed at the foot of the first slope. Fans and valley deposits may be formed in small tributary valleys or in the next lower valleys downstream without much contribution to the suspended load which travels farther downstream.

A procedure.--Any procedure will involve a study of the various types of erosion appearing to produce sediment. In a study of the sources of sediment, it is advisable to keep the types of erosion separated according to the treatments that might be recommended to reduce the erosion. If such a separation is maintained in the tabulations, the effects of the various treatments in reducing erosion, and thus reducing sediment yield, will be much easier to evaluate.

Different approaches may be employed to determine the relative sources of the sediment. A recommended procedure is to develop information as to what portion of the sediment yield is attributable to each of the various sources. Sediment delivery ratios should be estimated for the drainage areas above each reach or point of interest.

The sediment yield at the point of interest must be analyzed and proportioned to the available sources. By analysis of available data, study of the watershed and the use of sediment delivery ratios and estimates of erosion, a table such as table 6-1 can be developed to indicate the relative importance of sediment sources.

Table 6-1. Sediment sources (in percent of sediment yield).

| | Sheet Erosion | Gully Erosion | Road Banks | Stream Banks | Scour | Total Sediment yield |
|---|---|---|---|---|---|---|
| | % | % | % | % | % | % |
| reach 1 | 40 | 30 | 8 | 20 | 2 | 100 |
| reach 2 | 30 | 38 | 6 | 25 | 1 | 100 |
| reach 3 | 36 | 40 | 1 | 23 | - | 100 |

## Sediment Yield

### General

Sediment yield is equivalent to the gross erosion minus what is deposited enroute to the point of measurement. Sediment yield measurements or estimates are needed to evaluate sediment damage and sediment damage reduction and to determine sediment design requirements of structures. The yield of a given area varies with the changing patterns of precipitation, cover, and land use. For projection into the future, present sediment yields require adjustment for anticipated changes in these factors.

### Climatic factors

The influence of climatic factors such as precipitation, temperature and winds on sediment yields varies for different parts of the country.

Rainfall and correlative runoff is a primary factor in erosion throughout the country. Wind erosion is serious in some sections but is not as widespread as water erosion. The erosive power of rainfall depends upon its intensity, duration, and frequency. Seasonal distribution of rainfall is of prime importance in cropland areas because of the condition of the cover at the time of erosion-producing rainfall. Long duration rainfalls of low intensity are less erosive than intense, short duration storms. Guidance in computing long term sheet erosion rates may be found in chapter 3.

### Watershed factors

The important watershed factors affecting sediment yields are size of drainage area, topography, degree of channelization, soils, and cover conditions. The larger the drainage area in a given physiographic area, the larger the sediment yield. Generally, in a given physiographic area, the rate of sediment yield per unit of drainage decreases as the size of drainage area increases. However, in consistently mountainous areas, there is often no indicated difference in sediment yield per unit of area due to size of drainage area. Also, where active channel-type erosion increases downstream as from main-stem channel bank cutting, the sediment yield per unit of area may increase with increasing drainage area. Therefore, the relationship must be used with judgment and should be confined generally to the humid areas east of the Rocky Mountains.

There is less variation in the rate of sediment yield between large watersheds than among small ones. The mean rate of sediment yield decreases in much the same manner as runoff per unit of area decreases with increasing size of watersheds. The greater range of rates and the higher rates in small watersheds are chiefly caused by the shorter distances for sediment to be transported and less chance of counterbalancing high and low sediment producing areas. In other words, the small watershed tends to have more homogeneous land use or other watershed condition than the large one.

A small area with a low natural rate of erosion and with the land being used within its capability would have a low rate of sediment yield, and conversely high erosion rates are sharply reflected in high rates of sediment yield in the small watershed. In large watersheds the distances of sediment transport to downstream points being greater, the opportunities for deposition enroute are more numerous, so the size of the drainage area is an important factor in both the total sediment yield and the rate per square mile.

This relationship is complicated by many other factors such as rainfall, plant cover, texture of the sediment, and nature of land use. Therefore all of these factors must be evaluated in estimating volumes of sediment from an erosion source, rates of deposition in a proposed reservoir, or rates of sediment contribution to any downstream location.

A number of investigators have illustrated the relationship of watershed area to rates of sediment yield by means of graphs, curves, and charts. Among them are Gottschalk (1948), Brown (1950), Barnes (1953), Renfro (1954), and Roehl (1962).

Topography.-- The shape of the land surface is an inherent feature of the physiographic section in which the watershed is located. In addition, many of the problems of soil and water conservation depend on the situation in the individual watershed, especially what proportions of the area are upland, valley slope, flood plain, or include special features such as escarpments, canyons, or alluvial fans. Slope is a major factor affecting rates of on-site erosion, and watershed topography is an important factor affecting the delivery of eroded material.

The drainage pattern, amount of sloping land, and erosion rates are closely related to the stage of erosional development. Youthful areas are characterized by low slopes and relatively high proportions of high, nearly flat upland between stream valleys. Youthful watersheds at high elevations may have deep canyons along the principal streams, while youthful drainage of low glacial plains or other flat areas commonly has poorly developed stream courses and relatively low slopes. Watersheds in areas of old topography likewise have a relatively small amount of land in slope, but here the uplands are mostly eroded to low elevations and the greatest proportion of land is in old, broad valley flats. The highest proportion of sloping land occurs most commonly in mature areas, where drainage is well developed, and only limited areas of either uplands or valley flats are present. Therefore, average gradients and sediment yields tend to be higher in mature areas.

Channel density.-- The efficiency of a stream system to transport sediment out of a watershed is related to the degree of channelization. A watershed with a high channel density (total length of channel per unit of area) will have the most thorough water runoff and the most rapid and complete transportation of sediment from the area. Channel density can be measured on aerial photographs with the aid of a stereoscope.

Soils and cover conditions.-- Soils and cover are important factors influencing sediment yields from watersheds. The more erodible the soil and the sparser the vegetation, the higher the sediment yield, all other conditions being equal. The evaluation of sediment yields from watersheds of variable soils and mixed covers becomes quite complex and requires a procedure such as a soil-loss equation to determine erosion for the various soil-slope-cover delineations in the watershed. Sediment yields from single cover watersheds with more or less uniform conditions tend to be quite similar for watersheds of similar size, topography, and like cover.

Land use.-- According to the census of Agriculture adjusted to 1964, about 20 percent of the 2,266 million acres in the United States are cropland; 28 percent are grassland, pasture, and range; 34 percent are forest; 12 percent are marsh, bare rock, desert, and tundra; and the remaining 6 percent are residential, industrial, for transportation, and other special uses.

The land use is determined to some degree by the type of soil. In turn the land use determines to a large degree the type of cover. Where a watershed is primarily agricultural and has more than 20 inches of precipitation annually, a major part of the sediment yield is generally from sheet erosion. In most forest and range country and in areas with less than 20 inches of precipitation, channel-type erosion generally produces the greater part of the sediment (Brown, 1960).

The U. S. Department of Agriculture has found that conversion of forest land to continuous row crop cultivation increases erosion 100 to 10,000 fold. Plowing grassland for continuous row crop cultivation increases erosion 20 to 100 fold (Brown, 1960). Cultivated farm fields in the United States that lose more than 200 tons per acre per year from water erosion are not uncommon (Gottschalk and Jones, 1955) (Gottschalk, 1965). Small, intensely cultivated watersheds in western Iowa have had soil losses as high as 127,000 tons per square mile annually (Gottschalk and Brune, 1950).

Agricultural land with the broad area involved produces the most sediment but progress is being made in conserving this soil. Special uses create serious local problems. Examples are: 1) Urbanization--near Baltimore, an industrial park under construction produced at least 5 times the sediment concentration found in the waters immediately upstream (Wolman, 1964); areas under construction above Lake Barcroft,Va., and Lake Greenbelt, Md., yielded peak rates of 25,000 and 10,000 tons per square mile per year, respectively; 2) Strip mines--in Kentucky, a watershed with 10 percent of the area disturbed by active strip mining produced 57 times the sediment measured from a similar but undisturbed adjoining watershed (Collier, 1964); and 3) Highway construction--Vice (1969) reported sediment yields from such an area in Fairfax County, Va., were 10 times greater than for cultivated land, 200 times greater than for grass areas, and 2,000 times greater than for forest areas.

Methods of determining sediment yields

There are several ways to determine the sediment yield of a watershed depending on the environment and the data available. Average annual sediment yields may be obtained from: (1) gross erosion and sediment delivery ratios; (2) measured sediment accumulation; (3) sediment load records; and (4) predictive equations.

Gross erosion and sediment delivery ratios.-- This method has been used extensively and for many years by the SCS with success particularly in humid sections of the country. It is well suited for estimating current sediment yields and predicting the effect of land treatment and other measures on future sediment yields. The estimate of sediment yield is made by use of the following equation:

$$Y = E(DR)$$

where $Y$ = sediment yield (tons/unit area/year)
$E$ = gross erosion (tons/unit area/year)
$DR$ = sediment delivery ratio (DR less than 1)

The gross or total erosion in the drainage area is the summation of all the erosion taking place. It includes sheet and rill erosion and channel-type erosion (gullies, valley trenches, streambank erosion, etc.). The method of determination of the amount of each type of erosion is outlined in chapter 3 of this section 3 of the handbook and in existing guides and technical releases. The sediment delivery ratio is estimated from relationships discussed later in this chapter. The product of the gross erosion and sediment delivery ratio is the sediment yield.

Measured sediment accumulation.-- The measured sediment accumulation in reservoirs of known age and history are excellent sources of data for establishing sediment yields. Reservoir deposition and sediment yield are not synonymous. The amount of accumulated sediment must be divided by the reservoir's trap efficiency to obtain the sediment yield. This takes into account the amount of sediment that passed through the reservoir.

The sediment yield of an unmeasured watershed may be estimated from that of a measured watershed in the same major land resource area where the topography, soils, and land use are similar. In order to directly transpose sediment yield data, the size of the drainage area of the surveyed reservoir should not be less than one-half nor more than twice that of the watershed under consideration. Beyond these limitations the annual sediment yield may be adjusted on the basis of the ratio of the drainage areas raised to the 0.8 power:

$$S_e = S_m \left(\frac{A_e}{A_m}\right)^{0.8}$$

where $S_e$ = sediment yield of unmeasured watershed, in tons per year

$S_m$ = Sediment yield of measured watershed in tons per year (measured annual sediment deposition ÷ trap efficiency of surveyed reservoir)
$A_e$ = drainage area of unmeasured watershed
$A_m$ = drainage area of measured watershed

This relationship must be used with judgment and be confined generally to the humid areas east of the Rocky Mountains.

Occasionally sediment accumulated on fans and flood plains for a known period of time may be used as an indication of sediment yield, but this is best used as a verification of other methods. The procedures for measuring sediment in reservoirs or in valley deposits are discussed in chapter 7.

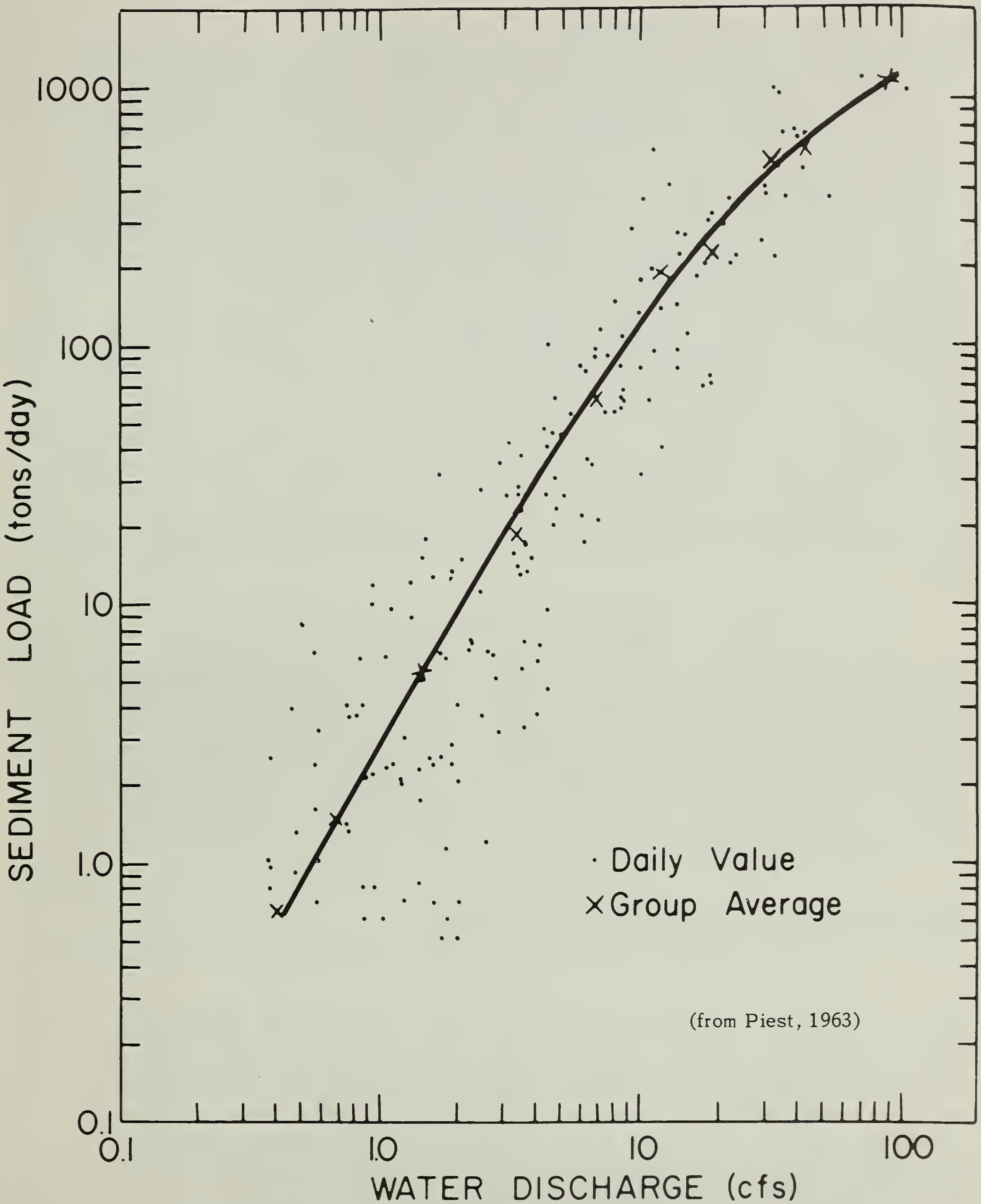
Suspended load records.-- Suspended sediment transported by a stream may be measured by sampling. Water discharge can be determined by gaging at particular stream cross sections. Sediment yields may be estimated from these data. Sediment concentration in milligrams per liter (or parts per million) is converted to tons per day by multiplying the average concentration and the volume of water discharged for the day of record and a conversion factor, usually 0.0027. Tons of sediment per day plotted vs. water discharge is a sediment rating curve. The data plotted on log-log paper will often approximate a straight line through at least a major part of the range of discharge. Such a line is shown in figure 6-1.

Using a flow duration curve or equivalent tabulations (Anderson, 1954) it is possible to approximate the average annual suspended sediment yield.

Usually the length of time required to collect a large enough range of suspended load data to prepare a sediment-rating curve prohibits the establishment of a suspended load station for small watersheds involved in SCS programs. However, if such suspended load records are available from nearby similar watersheds, they may be transposed in the same manner as reservoir sedimentation survey data (p. 6-7). The bed load portion of the sediment yield is not measured in this method and estimates of this part of the sediment load must be made. It can vary from practically none to as much as 50 percent or more of the total load depending on the type of sediment that is available for transport by the stream.

Predictive equations.-- Predictive equations based on watershed parameters have been developed in some areas to estimate sediment yield. These equations express sediment yield as a function of a combination of several measurable, independent variables. The variables may be the size of the drainage area, annual runoff, watershed shape, relief-length ratio, average slope, an expression of the particle size of the surface soil, and others.

Such equations are not numerous but, where developed, they may be used with the understanding that their application must be confined to the specific area they represent.




Direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 5, January 1957–December 1960

Figure 6-1 A Sediment Rating Curve

Sources of available information

Information on reservoir sedimentation surveys can be obtained from SCS reports and reports of other federal, state, and private agencies. Suspended load data for a wide range of watershed sizes, geographic areas, and quantity of streamflow are available from water supply papers and special reports of the U. S. Geological Survey. Many project reports of the Bureau of Reclamation and Corps of Engineers contain sediment yield data for particular drainage basins. Reports of the Inter-Agency Committee on Water Resources should be consulted, as well as River Basin Reports such as for the Missouri and Arkansas-White-Red Rivers. The Sedimentation Committee, Water Resources Council, periodically issues summaries of existing sedimentation surveys (FIARBC, 1953) (USDA, 1964) (USDA, 1969) and inventories of sediment load measurements (FIARBC, 1949) (FIARBC, 1952) (USGS, 1962) in the United States. Copies of these are available through the SCS representative on the committee. United Nations Flood Control Series bulletins contain some sediment yield data. Sediment yields to bottomlands, fans, bays, deltas, and other features are evaluated in many reports such as those listed above. Occasionally, sediment yield information is published in scientific and engineering journals (Gottschalk, 1965) (Holeman, 1968) (Diseker and Richardson, 1965).

## Sediment Delivery Ratios

The determination of the sediment delivery ratio is of primary importance to the geologist in order that he may provide realistic estimates of total sediment yield based on computed gross erosion. A characteristic relationship of sediment yield to erosion alone apparently does not exist. Many factors influence the sediment delivery ratio and unless all of these factors are uniform from watershed to watershed, the relation of sediment yield to erosion shows considerable variation.

Factors affecting sediment delivery ratios

Variations in sediment delivery ratios are dependent on some or all of the following influences and there may be others not yet identified.

Type of sediment sources.-- The type of sediment source affects the sediment delivery ratio. Channel-type erosion produces sediment that is immediately available to the transport system, and much of it tends to remain in motion as suspended sediment or bed load. Materials derived from sheet erosion, however, often move only short distances and may lodge in areas remote from the transport system. They may remain in the same fields in which they originated or be deposited on more level slopes as colluvium.

Magnitude and proximity of sediment sources.-- Another factor that will affect the sediment delivery ratio is the quantity of sediment available from a sediment source and the proximity of the source to streamflow. For example, a large amount of material is available from severe erosion in an area remote from the stream, but its

delivery ratio is less than that of a smaller amount of material made available by moderate erosion close to the stream. When the amount of sediment available for transport exceeds the capability of the transporting system deposition occurs and the sediment delivery ratio is decreased.

Transport system.-- Runoff resulting from rainfall and snowmelt is the chief agent for transporting eroded material. The ability to transport sediment is dependent on the velocity and volume of water discharge as well as the amount and character of the material supplied to it. The frequency and duration of discharges affect the total volume of sediment delivered. The extent and condition of the transport system have considerable bearing on the amount of sediment it can transport. A transport system with a high channel density has the greatest opportunity to transport eroded materials from the area and should indicate a high sediment delivery ratio. The condition of the channels--as clogged or open, meandering or straight--influences velocity and consequently the delivery ratio. High stream gradients are generally associated with steep slopes and high relief and provide efficient transport of eroded material. The converse is true for low stream gradients.

Texture of eroded material.-- The texture of the eroded material also influences sediment delivery ratios. If the eroded material is sand, efficient transport systems and relatively high velocities are necessary to transport it. Much of the eroded material of this type is deposited in the upstream areas wherever a significant drop in velocity occurs. Generally, it becomes a part of the sediment load only when the source areas are adjacent to an efficient transport system. If the material is fine silt and clay, it likely will stay in suspension as long as the water is moving and a large portion will be delivered to a downstream point. Some of the coarser particles of the generally fine-grained material may be deposited as colluvium prior to reaching the transport system. Often the larger grain-size materials are made available for transport by channel erosion while the silts and clays are generally made available by sheet erosion.

Depositional areas.-- Sometimes deposition occurs at the foot of upland slopes, along the edges of larger valleys, in valley flats, in and along main stream channels, and at the heads of and in reservoirs, lakes, and ponds. Such deposition within a watershed will decrease the amount of sediment delivered at points downstream from them.

Watershed characteristics.-- An important characteristic of a watershed is the size of the drainage area; the topography of a watershed also influences sediment delivery ratios. The shape of the land surface is an inherent feature of the physiographic section in which the watershed is located. Slope is a major factor affecting rates of onsite source erosion. High relief is often indicative of high sediment delivery ratios. The relief/length ratio apparently has a great effect on the sediment delivery ratio. For use in the R/L ratio the relief, measured in feet, is defined as the difference in elevation

between the average elevation of the watershed divide at the headwaters of the main stem drainage and elevation of the streambed at the point of sediment yield measurement. Length is defined as the maximum valley length, in feet, measured essentially parallel to the main stem drainage from the point of yield measurement to the watershed divide. The shape of a watershed will affect the sediment delivery ratio to some degree. Channel density also bears a relationship to the sediment delivery ratio but studies to date show that in any given land resource area, channel density and topography are closely related.

Procedures for estimating sediment delivery ratios

To determine an average sediment delivery ratio, the magnitude of the sediment yield at a given point in a watershed and the total amount of erosion must be known. Where such information is available, the determination of the sediment delivery ratio is a simple matter. However, measured data of both required items are not available in most small watersheds.

The gross erosion in a watershed can be estimated using standard SCS procedures (see chapter 3). Sediment yield can be determined by reservoir sedimentation surveys or by a program of sediment load measurements (see page 6-8).

Reservoirs frequently are not located at the points where sediment yields are needed, and a program of sediment load sampling may be a long-time and expensive procedure. However, if the ratio of known sediment yield and erosion within a homogeneous area can be analyzed in conjunction with some measurable influencing factor, such data can be used to predict or estimate sediment delivery ratios for similar areas where measured data are lacking.

In a given physiographic area, finding measurable influencing factors that can be definitely related to sediment delivery ratios is the goal of any delivery ratio analysis. As pointed out in the preceding discussion there are many factors that may influence sediment delivery ratios. Some are more pronounced in their effect than others. Some lend themselves to quantitative expression while others do not.

An effective means of developing information for use in estimating sediment delivery ratios is by statistical analysis using the sediment delivery ratio as a dependent variable and measurable watershed factors as the independent, or controlling variables. In such an analysis, quantitative data concerning sediment yields, erosion and measurable watershed factors must be available. Reservoir sedimentation surveys afford a source of sediment yield data. Erosion information can be developed as previously mentioned, and watershed factors can be determined from available maps or by field survey. These data can be analyzed to develop a means for estimating unknown sediment delivery ratios for similar areas. Analyses of this type are recommended to be made in consultation with the E&WP Unit watersheds geologists.

Size of drainage area.-- An analysis of data obtained from past studies[1] is presented in figure 6-2. This general curve is based on data that indicate a wide variation in sediment delivery ratios for any given drainage area size. This analysis of data from widely scattered areas does, however, show that there evidently is some similarity in the sediment delivery ratios throughout the country and, roughly, that they vary inversely as the 0.2 power of the drainage area. Rough estimates of sediment delivery ratios can be made through the use of figure 6-2, but any such estimate should be tempered with judgment and consideration of other influencing factors such as texture, relief, type of erosion, the sediment transport system, and areas of deposition within the drainage area. As an example, when the texture of the upland soils is essentially silt or clay, the sediment delivery ratio (percent of erosion) will be higher than indicated in figure 6-2; and when the soil texture is coarse, the sediment delivery ratio will be lower than the line shown.

Somewhat more refined sediment delivery ratio- drainage area relationships have been developed by regions at some E&WP Units and may be used in place of figure 6-2.

Relief-length ratio.-- The watershed relief-length ratio has been shown by several investigators (Maner, 1953; Roehl, 1962) as a significant indicator of the sediment delivery ratio. Empirical equations were developed to estimate the R/L ratio for the Red Hills of Texas, Oklahoma, and Kansas and for the Southern Piedmont Region of the Southeast. The effect of the R/L ratio may not be as pronounced in some areas as in others; but as it is related to and seems to be a reasonable expression of several measurable watershed factors, further studies of this parameter to extend its usefulness to other physiographic areas are desirable.

Source-texture analysis.-- In all of the preceding discussion concerning means of estimating sediment delivery ratios, the delivery ratios are percentages of total erosion. Many times the individual delivery ratio of the component parts of the total erosion is of concern to the geologist. Reasonable and realistic values of the delivery of component parts must be estimated from scanty data. One means of developing such estimates is by making certain determinations or assumptions concerning the source of various components of a known sediment yield.

The following is an example using the source-texture analysis method: The amount of sediment created in the watershed from different sources or types of erosion is computed in tons per year. These sediment sources are sheet erosion, gullies, road banks and ditches, and receding streambanks. The suspended sediment yield of the watershed is determined by sampling. The bed load is estimated by judgment as a percent of the suspended sediment yield. The bed load consists of

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1/ Gottschalk and Brune (1950), Woodburn and Roehl (1951), Maner and Barnes (1953), Glymph (1954), Maner (1957), and Roehl (1962).

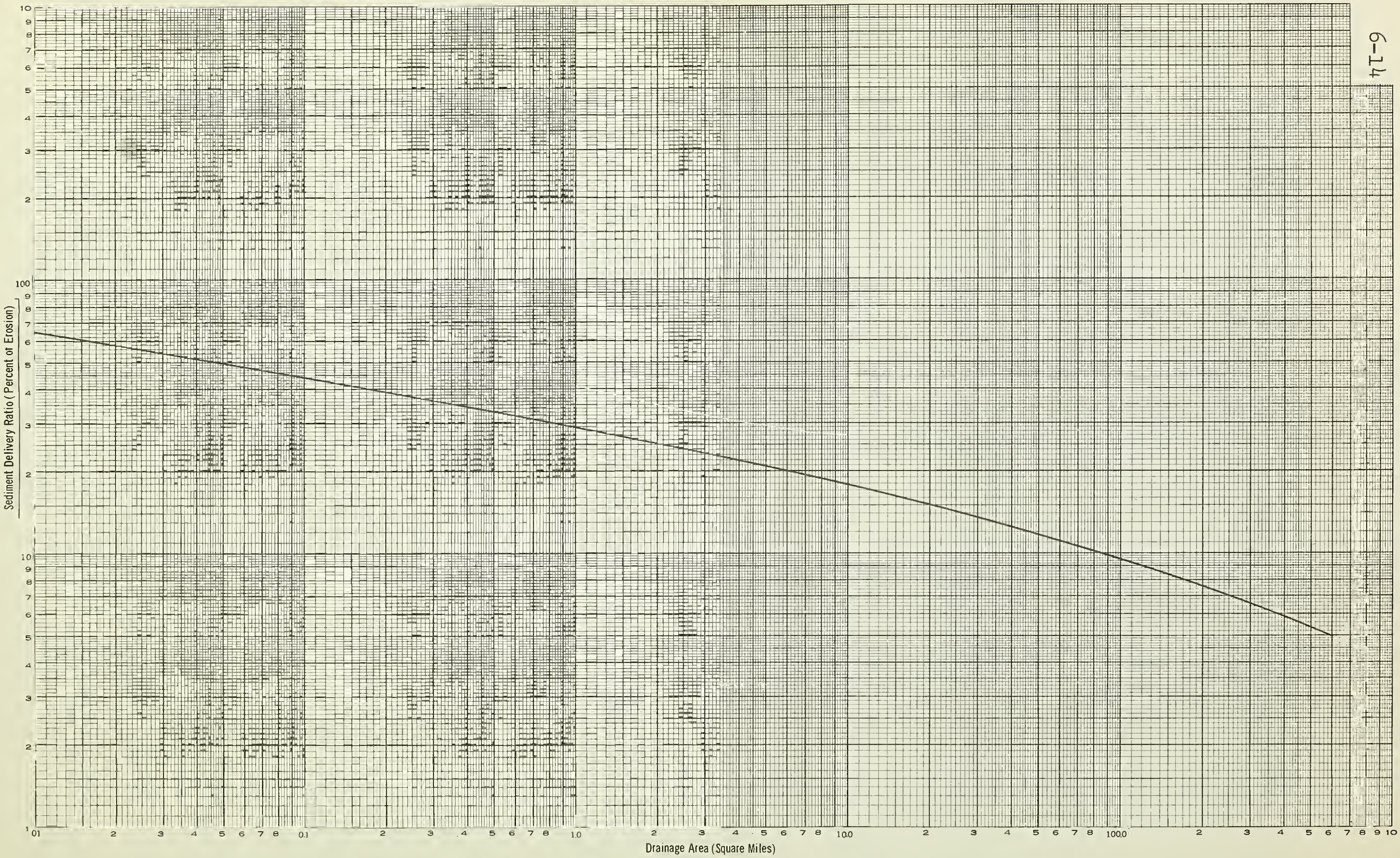


FIGURE 6—2. Sediment delivery ratio vs. size of drainage area

sand and the suspended load fines. The bed of the stream is in equilibrium, therefore, the bed itself is not considered a net source of sediment under present conditions. Considering the texture of the sediment and the texture of the material available in the various sources, it is assumed that all of the sand will be made available from gullies, road banks and ditches, and the fine materials will be made available from the receding streambanks and sheet erosion. A further assumption is made that 100 percent of the streambank material will be delivered to the point of measurement.

By comparing the amount of sand being carried past the point of measurement with the volume of material made available by gullies and road banks and ditches, a delivery ratio for the gullies and roadside erosion is established. The volume of fine material available from the receding streambanks accounts for its part of the suspended load. The remainder of the suspended load is that portion of the material contributed by sheet erosion thus the delivery ratio of sheet erosion materials is developed. Table 6-2 illustrates this method of estimating sediment delivery ratios from the component parts of the sediment source.

Table 6-2. Sediment source and delivery ratio.

| Sediment Source | Erosion[1/] | | Sediment Yield[2/] | | Delivery Ratio |
|---|---|---|---|---|---|
| | Sand | Fines | Sand | Fines | |
| | Tons/Yr | Tons/Yr | Tons/Yr | Tons/Yr | Percent |
| Sheet Erosion | -- | 900,000 | -- | 300,000[3/] | 33 |
| Channel Erosion | | | | | |
| Gullies | 350,000 | -- | 280,000 | -- | 80[4/] |
| Road Banks | 150,000 | -- | 120,000 | -- | 80[4/] |
| Streambanks | -- | 900,000 | -- | 900,000 | 100 |
| TOTAL | 500,000 | 1,800,000 | 400,000[5/] | 1,200,000[6/] | 70 |

1/ Determined by standard SCS procedures.
2/ Assumed that all fines are from sheet erosion and streambanks, and all sand from gullies and road banks.
3/ Difference between total yield of fines and yield of fines from streambanks.
4/ Computed as ratio of total sand yield to total sand available. Assumed equal delivery ratio for gullies and roadbanks.
5/ The bed load is estimated as a percent of the suspended load.
6/ Determined from suspended load measurements.

By this procedure estimates of sediment delivery ratios can be made that are usable in similar areas. It must be recognized that many broad assumptions are required in an analysis of this type, and that the results are subject to considerable error.

Source-deposition.-- Another means of developing sediment delivery ratios is by field study of a watershed and estimating the amount of deposition that can be traced to its source. The difference in the volume of such deposition and the volume supplied by the source will give an estimate of the delivery ratio from that source.

Summary

In many instances measured basic data upon which to base detailed analyses are insufficient or entirely lacking. The validity of using an equation for obtaining sediment data beyond the physiographic area for which it was developed is questionable and generally not recommended. Yet a knowledge of sediment delivery ratios is needed by the geologist to determine sediment yields, to ascertain the relative importance of various sediment sources, and to recommend measures to reduce sediment yields.

Most areas in the country do have information concerning the total sediment yield from some watersheds. Such data are available from suspended load records and reservoir sedimentation survey records. The comparison of the sediment yield and the calculated gross erosion will give indications of an expected sediment delivery ratio for the area. Such an analysis is much broader than detailed studies. Transposing such estimates to other like areas is subject to error.

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SECTION 3

SEDIMENTATION

# CHAPTER 10. UNITS AND EQUIVALENTS

## General

Various lists, tables, and charts are included in this section for the convenience of the geologists in compiling information on rates, volumes, and quantities of sediment, rock formations, and geologic processes. The only explanation in the tables and charts is that which is necessary to give the basis of the information presented. The conversion factors are generally shown for 4 significant digits suitable for field use with a slide rule. For office calculations, more precise conversion factors of 5 or more significant digits may be needed in some instances.

## Conversion Factors

| To Convert | Into | Multiply By |
|---|---|---|
| | A | |
| acre | hectare or sq hectometer | .4047 |
| | sq feet (sq ft) 1/ | 43,560. |
| | sq meters (sq m) | 4,047. |
| | sq miles (sq mi) | $1.562 \times 10^{-3}$ |
| acre-ft | cu ft | 43,560. |
| | cu yds | 1,613. |
| | gallons (gal) | 325,850. |
| | cu meters (cu m) | 1,234. |
| acre-ft/sq mi | cu ft/acre | 68.06 |

1/ These abbreviations may be used when their meaning is clear; otherwise spell them out. Do not use a period after abbreviations except for in.

| To Convert | Into | Multiply By |
|---|---|---|
| acre-ft/sq mi | tons/sq mi | See Fig. 10-1 |
| | tons/acre | 2/ |
| | watershed inches | .01875 |
| | cu meters/sq km (cu m/sq km) | 476.3 |
| acre-ft of water | tons | 1,359. |
| acre-inch | acre-ft | .08333 |
| | cu ft | 3,630. |

C

| To Convert | Into | Multiply By |
|---|---|---|
| Celsius or Centigrade (C) | Fahrenheit (F) | 1.8C + 32 |
| centimeters (cm) | feet (ft) | 0.03281 |
| | inches (in.) | 0.3937 |
| | meters (m) | 0.01 |
| | millimeters (mm) | 10.0 |
| centimeters/sec (cps) | ft/min | 1.197 |
| cubic centimeters (cc) | cu ft | $3.531 \times 10^{-5}$ |
| | cu in. | 0.06102 |
| | U.S. gallons (U.S. gal) | $2.642 \times 10^{-4}$ |
| | liters (l) | 0.001 |
| | U.S. pints | $2.113 \times 10^{-3}$ |
| | U.S. quarts | $1.057 \times 10^{-3}$ |
| cubic feet (cu ft) | cu cms (cc) | 28,320. |
| | cu in. | 1,728. |
| | cu meters (cu m) | 0.02832 |
| | cu yards (cu yd) | 0.03704 |
| | U.S. gallons | 7.481 |
| | liters (l) | 28.32 |

2/ After getting tons/sq mi from Fig. 10-1, multiply by $1.56 \times 10^{-3}$ to convert to tons/acre.

| To Convert | Into | Multiply By |
|---|---|---|
| cu ft/acre | inches-depth (in.-depth) | $2.754 \times 10^{-3}$ |
| cubic feet of water | pounds (lbs) | 62.43 |
| | kgs/sq cm | 0.03048 |
| | kgs/sq meter (kgs/sq m) | 304.8 |
| | pounds/sq ft (psf) | 62.43 |
| | pounds/sq in. (psi) | 0.4335 |
| cubic feet/sec (cfs) | acre-ft per day (ac-ft/d) | 1.984 |
| | acre-ft per year (ac-ft/yr) | 724.0 |
| | million gal's/day (mgd) | 0.6463 |
| | cu m/sec | 0.02832 |
| cu ft/sec/sq mi (csm) | liters/sec/sq km (l/sec/sq km) | 0.0915 |
| cubic ft/sec (cfs) | gallons/min (gpm) | 448.8 |
| cfs-days | cu ft | 86,400. |
| cubic inches (cu in.) | cu cms (cc) | 16.39 |
| | cu ft | $5.787 \times 10^{-4}$ |
| cubic meters (cu m) | cu ft | 35.32 |
| | U.S. gallons (U.S. gal) | 264.2 |
| | cubic yards (cu yd) | 0.7645 |
| cu m/sq km | ac-ft/sq mi | $21.0 \times 10^{-4}$ |
| cu mi (U.S. statute) | acre-ft | $3.379 \times 10^{6}$ |
| cubic yards (cu yd) | cu cms (cc) | $7.646 \times 10^{5}$ |
| | cu ft | 27.0 |
| | cu meters (cu m) | 0.7646 |
| | U.S. gallons (U.S. gal) | 202.0 |
| | acre-ft | $6.19 \times 10^{-4}$ |

D

| | | |
|---|---|---|
| days | seconds (sec) | 86,400. |
| deg F | deg C (Centigrade or Celsius) | $(F^{\circ} - 32).5556$ |

| To Convert | Into | Multiply By |
|---|---|---|
| | F | |
| Fahrenheit (F) | Centigrade (C) | $(F^{\circ} - 32).5556$ |
| fathoms (fthm) | meter (m) | 1.829 |
| | feet (ft) | 6.000 |
| feet (ft) | centimeters (cm) | 30.48 |
| | kilometers (km) | $3.048 \times 10^{-4}$ |
| | meters (m) | 0.3048 |
| | miles (mi) | $1.894 \times 10^{-4}$ |
| feet/min (fpm) | cms/sec (cps) | 0.5080 |
| | feet/sec (fps) | 0.01667 |
| | kms/hour (km/hr) | 0.01829 |
| | miles/hour (mi/hr) | 0.01136 |
| feet/sec (fps) | meters/min (m/min) | 18.29 |
| | miles/hour (mph) | 0.6818 |
| | km/hour (km/hr) | 1.097 |
| | G | |
| gal U.S. | cubic cms (cc) | 3,785.0 |
| | cubic feet (cu ft) | 0.1337 |
| | cubic inches (cu in.) | 231.0 |
| | gallons Br. Imp. (gal Br. Imp.) | 0.8327 |
| | liters (l) | 3.785 |
| gallons of water | pounds of water | 8.3453 |
| gallons/min (gpm) | cu ft/sec (cfs) | $2.228 \times 10^{-3}$ |
| | liters/sec (l/sec) | 0.06308 |
| | cu ft/hr | 8.0208 |
| grams (g) | pounds (lbs) | $2.205 \times 10^{-3}$ |
| gram of water | cu cm of water (cc of wtr) | 1.0 (at 4°C) |

| To Convert | Into | Multiply By |
|---|---|---|
| | H | |
| hectares | acres | 2.471 |
| | sq feet (sq ft) | $1.076 \times 10^5$ |
| hours (hr) | days | .04167 |
| | weeks (wk) | $5.952 \times 10^{-3}$ |
| | I | |
| inches (in.) | centimeters (cm) | 2.540 |
| inches (watershed) | cu ft/sec/sq mi (csm) | 13.584 |
| inches eroded | tons | 1.815 x volume wt (pcf) of upland soil |
| | K | |
| kilograms (kg) | pounds, (lb) avoirdupois | 2.205 |
| | tons, short (T) | $1.102 \times 10^{-3}$ |
| kilograms/sec(kg/sec) | tons (short)/year (T/yr) | 34,786. |
| kilometers (km) | miles (mi) | 0.6214 |
| | L | |
| liters (l) | cubic cm (cc) | 1,000. |
| | gallons U.S. (gal U.S.) | 0.2642 |
| liters/sec/sq km | cubic ft/sec/sq mi (csm) | 10.93 |
| | M | |
| meters (m) | yards (yd) | 1.094 |
| | feet (ft) | 3.281 |
| | inches (in.) | 39.37 |

| To Convert | Into | Multiply By |
|---|---|---|
| meters (m) | miles (stat) (mi stat) | $6.214 \times 10^{-4}$ |
| microns (μ) | meters (m) | $1.0 \times 10^{-6}$ |
| miles(U.S. stat)(mi) | kilometers (km) | 1.609 |
| miles/hour (mph) | feet/sec (fps) | 1.467 |
| milligrams/liter(mg/l) | parts/million (ppm) | 1.000 3/ |
| milliliters (ml) | liters (l) | 0.001 |
| millimeters (mm) | inches (in.) | 0.03937 |
| | microns (μ) | $1 \times 10^3$ |
| million gallons/day(mgd) | cu ft/sec (cfs) | 1.547 |
| | acre-ft/day | 3.069 |
| | cu m/min | 2.629 |
| minutes (min)(angles) | degrees (deg) | 0.01667 |

O

| | | |
|---|---|---|
| ounces (oz) | grams (g) | 28.35 |
| | pounds (lb) | 0.0625 |
| ounces/gallon(U.S.) (oz/gal-U.S.) | gms/liter (gm/l) | 7.489 |

P

| | | |
|---|---|---|
| parts per million (ppm) | milligrams per liter (mg/l) | 1.000 3/ |
| pounds (lb) | grains | 7,000. |
| | grams (g) | 453.6 |
| | kilograms (kg) | 0.4536 |
| | ounces (oz) | 16.00 |
| | tons 4/ | .0005 |

3/ True within 1 percent when the concentration is less than 10,000 ppm.

4/ Tons means short tons (2000 lbs) unless otherwise indicated, as tons (metric) or tons (long).

| To Convert | Into | Multiply By |
|---|---|---|
| pounds of water | cubic feet (cu ft) | 0.01602 |
| | cubic inches (cu in.) | 27.68 |
| | gallons (gal) | 0.1198 |
| pounds of water/min | cu ft/sec (cfs) | $2.670 \times 10^{-4}$ |
| pounds/cu foot(pcf) | grams/cu cm (g/cc) | 0.01602 |
| | kgs/cu meter (kg/cu m) | 16.02 |
| | pounds/cu in. (pci) | $5.787 \times 10^{-4}$ |
| pounds/cu in. | gms/cu cm (g/cc) | 27.68 |
| pounds/gallon (U.S.) | gms/liter (g/l) | 119.8 |
| pounds/cu foot (pcf) | tons/acre-foot(tons/acre-ft) | 21.78 |
| pounds/sq foot(psf) | pounds/sq in. (psi) | $6.944 \times 10^{-3}$ |
| | R | |
| rods | feet(ft) | 16.50 |
| | miles | $3.125 \times 10^{-3}$ |
| | S | |
| sq centimeters(sq cm) | square inches (sq in.) | 0.1550 |
| square feet (sq ft) | acres | $2.296 \times 10^{-5}$ |
| square inches(sq in.) | sq cms | 6.452 |
| sq kilometers(sq km) | sq miles (sq mi) | 0.3861 |
| square meters (sq m) | sq ft | 10.76 |
| square miles (sq mi) | acres | 640.0 |
| | square feet (sq ft) | $27.88 \times 10^{6}$ |
| | square kms (sq km) | 2.590 |
| | square meters (sq m) | $2.590 \times 10^{6}$ |
| | square yards (sq yd) | $3.098 \times 10^{6}$ |
| square yards (sq yd) | square feet (sq ft) | 9.000 |
| | square meters (sq m) | 0.8361 |

| To Convert | Into | Multiply By |
|---|---|---|
| | T | |
| tons (long) | pounds | 2,240. |
| tons (metric) | kilograms (kg) | 1,000. |
| | tons | 1.102 |
| | pounds (lbs) | 2,205. |
| tons (metric)/sq km | tons/sq mi | 2.854 |
| tons | kilograms (kgs) | 907.2 |
| | pounds (lbs) | 2,000. |
| | tons (long) | 0.8929 |
| | tons (metric) | 0.9078 |
| tons/sq mi | acre-ft/sq mi | see Fig. 10-1A and B |
| | tons(metric)/sq km | 0.350 |
| | tons/acre | $1.5625 \times 10^{-3}$ |
| tons of water/24 hrs | pounds of water/hour | 83.33 |
| | gallons/min (gpm) | 0.1664 |
| | cu ft/hr | 1.335 |
| tons/acre-ft | pounds/cu ft (pcf) | 0.04591 |
| | W | |
| watershed in. | acre-ft/sq mi | 53.33 |
| watershed inches | acre-ft (total) | 53.33 x drainage area (in sq mi) |
| | Y | |
| years (yr) | seconds (sec) | $31.5576 \times 10^{6}$ |

Figures 10-1A and 10-1B are charts for converting various volume weights or weights of sediment per acre-foot to tons. Table 10-1 below is convenient for the conversion of various volumes of hydraulic or sedimentation data. Table 10-2 is the Greek alphabet. Table 10-3 shows map scales and equivalents for use with aerial photographs and USGS quadrangles. Table 10-4 illustrates conversions in volume weight between pounds per cubic foot and tons per acre foot. Table 10-5 converts inches to feet.

Table 10-1. Conversion factors for hydraulic volumes

| Initial unit | Multiplier to obtain: | | | | |
|---|---|---|---|---|---|
| | Cfs-days | Cu ft x $10^6$ | Gal x $10^6$ | Acre-ft | In./sq mi |
| Cfs-days | - | 0.08640 | 0.64632 | 1.9835 | 0.037190 |
| Cu ft x $10^6$ | 11.574 | - | 7.4805 | 22.957 | .43044 |
| Gal x $10^6$ | 1.5472 | .13368 | - | 3.0689 | .05742 |
| Acre-ft | .50417 | .04356 | .32585 | - | .018750 |
| In./sq mi | 26.889 | 2.3232 | 17.379 | 53.33 | - |

Table 10-2. Greek Alphabet

| | | | |
|---|---|---|---|
| Α α Alpha | Η η Eta | Ν ν Nu | Τ τ Tau |
| Β β Beta | Θ θ Theta | Ξ ξ Xi | Υ υ Upsilon |
| Γ γ Gamma | Ι ι Iota | Ο ο Omicron | Φ φ Phi |
| Δ δ Delta | Κ κ Kappa | Π π Pi | Χ χ Chi |
| Ε ε Epsilon | Λ λ Lambda | Ρ ρ Rho | Ψ ψ Psi |
| Ζ ζ Zeta | Μ μ Mu | Σ σ Sigma | Ω ω Omega |

Suspended Sediment and Sediment Yield

Conversion of parts per million by weight to sediment yield in tons:

$$\frac{\text{ppm x discharge (cu ft per period) x 62.4}}{\text{1,000,000 x 2,000 (or 2 x }10^9)} = \text{sediment load (tons per period)}$$

Table 10-3. Map Scales and Area Equivalents

Aerial Photographs and USGS Quadrangles

| Fractional Scale | Feet Per Inch | Inches[1] Per Mile | Acres Per Sq Inch | Sq Inches Per Acre | Sq Mile Per Sq In. |
|---|---|---|---|---|---|
| 1:600 | 50.00 | 105.60 | 0.0574 | 17.424 | 0.00009 |
| 1:1200 | 100.00 | 52.80 | 0.2296 | 4.356 | 0.00036 |
| 1:2400 | 200.00 | 26.40 | 0.9183 | 1.089 | 0.0014 |
| 1:3600 | 300.00 | 17.60 | 2.0661 | 0.484 | 0.0032 |
| 1:4800 | 400.00[2] | 13.20 | 3.6731 | 0.272 | 0.0057 |
| 1:6000 | 500.00 | 10.56 | 5.7392 | 0.174 | 0.0090 |
| 1:7200 | 600.00 | 8.80 | 8.2645 | 0.121 | 0.0129 |
| 1:7920 | 660.00 | 8.00[2] | 10.000 | 0.100 | 0.0156 |
| 1:9600 | 800.00 | 6.60 | 14.692 | 0.068 | 0.0230 |
| 1:12000 | 1000.00 | 5.28 | 22.957 | 0.044 | 0.0359 |
| 1:15840 | 1320.00 | 4.00[2] | 40.000 | 0.025 | 0.0625 |
| 1:20000[2] | 1666.67 | 3.168[2] | 63.769 | 0.157 | 0.0996 |
| 1:24000[3] | 2000.00 | 2.640 | 91.827 | 0.011 | 0.1435 |
| 1:31680[3] | 2640.00 | 2.000 | 160.000 | 0.006 | 0.2500 |
| 1:62500[3] | 5208.33 | 1.014 | 622.744 | 0.0016 | 0.9730 |
| 1:63360[3] | 5280.00 | 1.000 | 640.00 | 0.0016 | 1.0000 |
| 1:125000[3] | 10416.67 | 0.507 | 2490.98 | 0.0004 | 3.8922 |
| 1:126720[3] | 10560.00 | 0.500 | 2560.00 | 0.0004 | 4.0000 |
| 1:250000[3] | 20933.33 | 0.253 | 9963.91 | 0.0001 | 15.5686 |
| 1:500000[3] | 41666.67 | 0.127 | 39855.63 | 0.000025 | 62.2744 |
| Formulas | $\frac{\text{scale}}{12}$ | $\frac{63360}{\text{scale}}$ | $\frac{(\text{scale})^2}{43560 \times 144}$ | $\frac{43560 \times 144}{(\text{scale})^2}$ | $\frac{(\text{ft per in.})^2}{(5280)}$ |

1/ To determine miles per inch divide scale by 63360.
2/ common aerial photograph scales
3/ common USGS Quadrangle scales

Table 10-4. Volume-Weight Conversions

1 $lb/ft^3 \doteq .0005\ tons/ft^3$; $lb/ft^3 \times 21.78 = tons/ac\text{-}ft$

| lbs/$ft^3$ | tons/$ft^3$ | tons/ac-ft | lbs/$ft^3$ | tons/$ft^3$ | tons/ac-ft |
|---|---|---|---|---|---|
| 100 | .0500 | 2178.0 | 79 | .0395 | 1720.6 |
| 99 | .0495 | 2156.2 | 78 | .0390 | 1698.8 |
| 98 | .0490 | 2134.4 | 77 | .0385 | 1677.1 |
| 97 | .0485 | 2112.7 | 76 | .0380 | 1655.3 |
| 96 | .0480 | 2090.9 | 75 | .0375 | 1633.5 |
| 95 | .0475 | 2069.1 | 74 | .0370 | 1611.7 |
| 94 | .0470 | 2047.3 | 73 | .0365 | 1589.9 |
| 93 | .0765 | 2025.5 | 72 | .0360 | 1568.2 |
| 92 | .0460 | 2003.8 | 71 | .0355 | 1546.4 |
| 91 | .0455 | 1982.0 | 70 | .0350 | 1524.6 |
| 90 | .0450 | 1960.2 | 69 | .0345 | 1502.8 |
| 89 | .0445 | 1938.4 | 68 | .0340 | 1481.0 |
| 88 | .0440 | 1916.6 | 67 | .0335 | 1459.3 |
| 87 | .0435 | 1894.9 | 66 | .0330 | 1437.5 |
| 86 | .0430 | 1873.1 | 65 | .0325 | 1415.7 |
| 85 | .0425 | 1851.3 | 64 | .0320 | 1393.9 |
| 84 | .0420 | 1829.5 | 63 | .0315 | 1372.1 |
| 83 | .0415 | 1807.7 | 62 | .0310 | 1350.4 |
| 82 | .0410 | 1786.0 | 61 | .0305 | 1328.6 |
| 81 | .0405 | 1764.2 | 60 | .0300 | 1306.8 |
| 80 | .0400 | 1742.4 | | | |

| lbs/$ft^3$ | tons/$ft^3$ | tons/ac-ft | lbs/$ft^3$ | tons/$ft^3$ | tons/ac-ft |
|---|---|---|---|---|---|
| 59 | .0295 | 1285.0 | 39 | .0195 | 849.4 |
| 58 | .0290 | 1263.2 | 38 | .0190 | 827.6 |
| 57 | .0285 | 1241.5 | 37 | .0185 | 805.9 |
| 56 | .0280 | 1219.7 | 36 | .0180 | 784.1 |
| 55 | .0275 | 1197.9 | 35 | .0175 | 762.3 |
| 54 | .0270 | 1176.1 | 34 | .0170 | 740.5 |
| 53 | .0265 | 1154.3 | 33 | .0165 | 718.7 |
| 52 | .0260 | 1132.6 | 32 | .0160 | 6 7.0 |
| 51 | .0255 | 1110.8 | 31 | .0155 | 075.2 |
| 50 | .0250 | 1089.0 | 30 | .0150 | 653.4 |
| 49 | .0245 | 1067.2 | 29 | .0145 | 631.6 |
| 48 | .0240 | 1045.4 | 28 | .0140 | 609.8 |
| 47 | .0235 | 1023.7 | 27 | .0135 | 588.0 |
| 46 | .0230 | 1001.9 | 26 | .0130 | 566.3 |
| 45 | .0225 | 980.1 | 25 | .0125 | 544.5 |
| 44 | .0220 | 458.3 | 24 | .0120 | 522.7 |
| 43 | .0215 | 936.5 | 23 | .0115 | 500.9 |
| 42 | .0210 | 914.8 | 22 | .0110 | 479.2 |
| 41 | .0205 | 893.0 | 21 | .0105 | 457.4 |
| 40 | .0200 | 871.2 | 20 | .0100 | 435.6 |

1 acre-foot = 43,560 cu ft = 1,613.33 cu yds
1 day = 24 hours = 1440 minutes = 86,400 seconds

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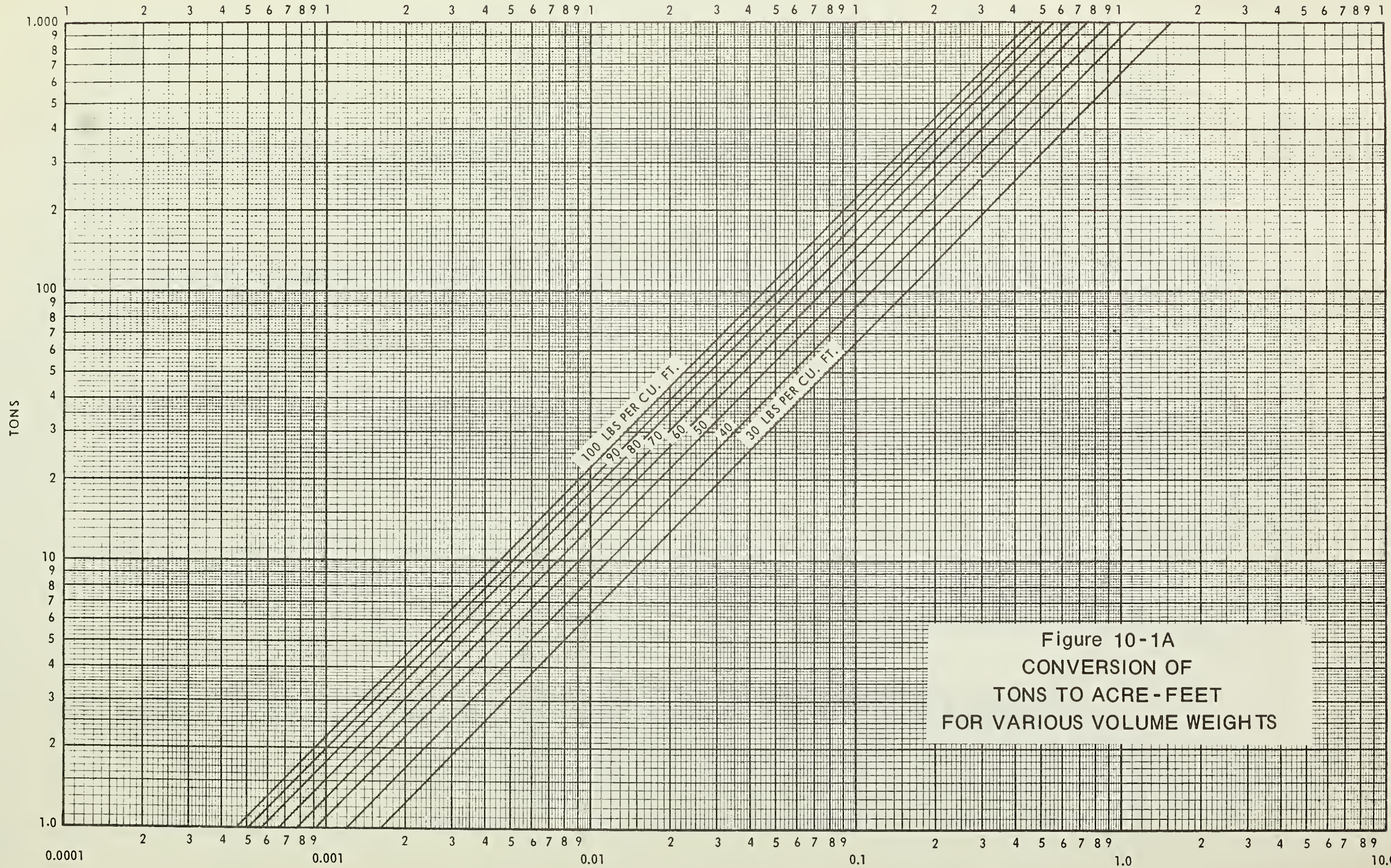


Figure 10-1A
CONVERSION OF
TONS TO ACRE-FEET
FOR VARIOUS VOLUME WEIGHTS

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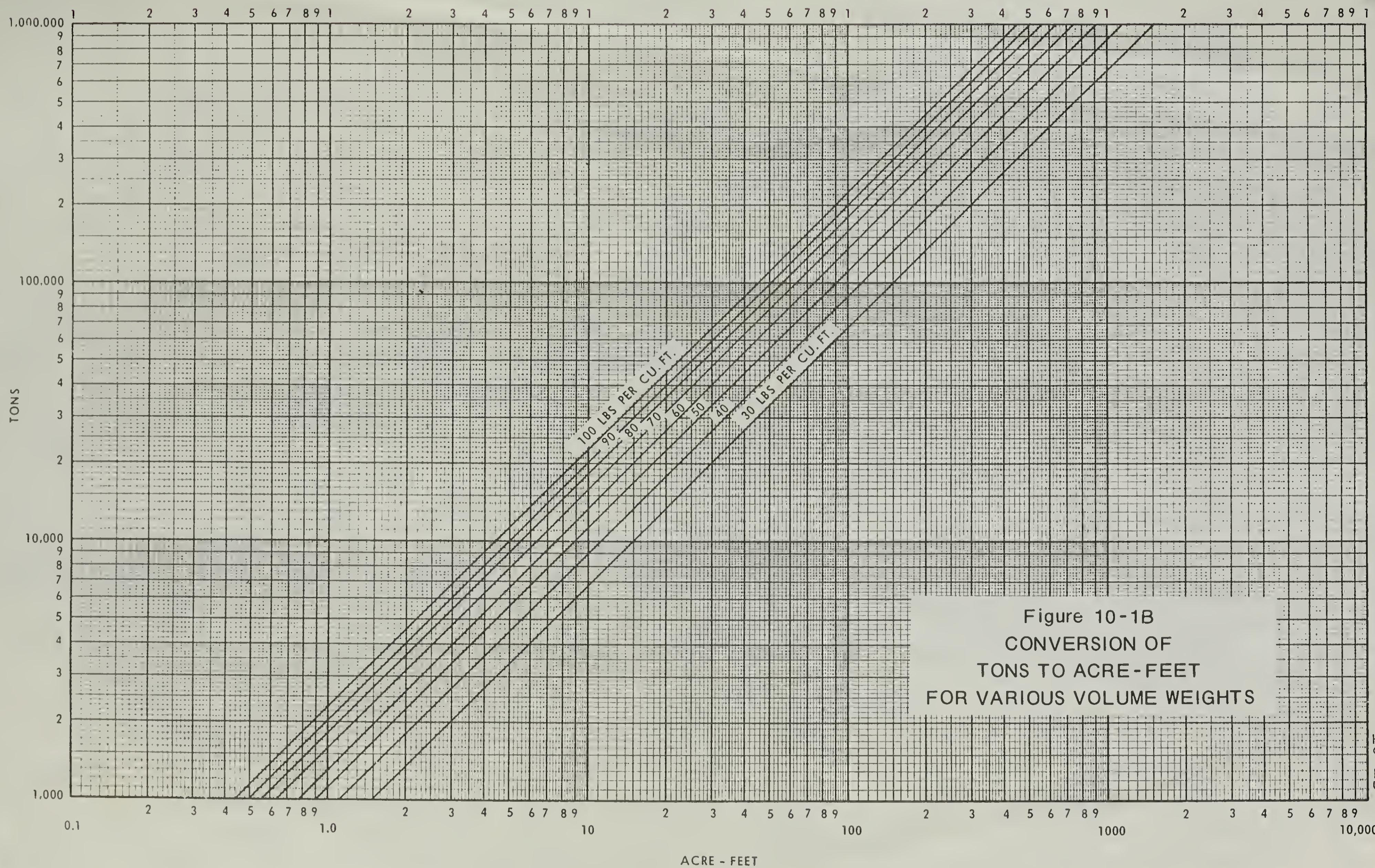


Figure 10-1B
CONVERSION OF
TONS TO ACRE-FEET
FOR VARIOUS VOLUME WEIGHTS

Table 10-5. A conversion of inches to feet

| | |
|---|---|
| 1 in. = 0.08 ft | 7 in. = 0.58 ft |
| 2 in. = 0.17 ft | 8 in. = 0.67 ft |
| 3 in. = 0.25 ft | 9 in. = 0.75 ft |
| 4 in. = 0.33 ft | 10 in. = 0.83 ft |
| 5 in. = 0.42 ft | 11 in. = 0.92 ft |
| 6 in. = 0.50 ft | 12 in. = 1.00 ft |

## References

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